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MILITARY HANDBOOK

PLASTIC MATERIAL PROPERTIES FOR ENGINEERING DESIGN



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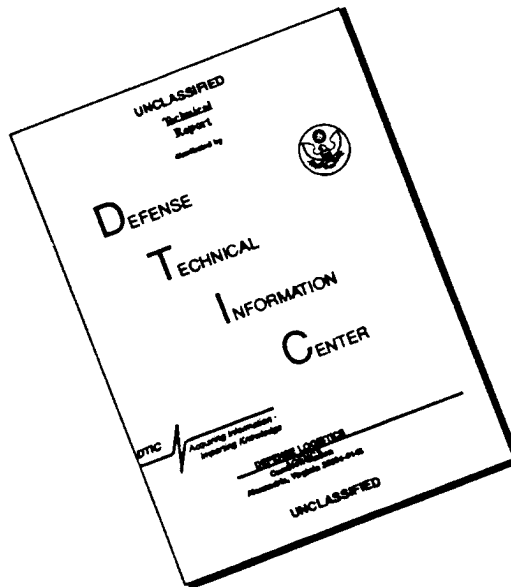
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FOREWORD

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3. This handbook was developed under the auspices of the US Army Materiel Command's Engineering Design Handbook Program, which is under the direction of the US Army Industrial Engineering Activity.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABS = acrylonitrile-butadiene-styrene	OSU = Ohio State University
AMCP = Army Materiel Command Pamphlet	PCTFE = polychlorotrifluoroethylene
AMMRC = Army Materials and Mechanics Research Center	PF = power factor
ANSI = American National Standards Institute	PTFE = polytetrafluoroethylene
ASTM = American Society for Testing and Materials	PV = pressure times velocity
CIE = International Commission of Illumination	PVC = polyvinyl chloride
DARCOM = US Army Materiel Development and Readiness Command	SAE = Society of Automotive Engineers
DoD = Department of Defense	SAMPE = Society of Aerospace Material and Process Engineers
DP = degree of polymerization	SIC = specific inductive capacity
DSC = differential scanning calorimetry	SPE = Society of Plastics Engineers
DTA = differential thermal analysis	SPIE = Society of Photo-Optical Instrumentation Engineers
ESC = environmental stress cracking	TDP = technical data package
FEP = fluorinated ethylenepropylene	T _g = glass transition temperature
IEEE = Institute of Electrical and Electronics Engineers, Inc.	TGA = thermogravimetric analysis
NIST = National Institute of Standards and Technology	TMA = thermomechanical analysis
NMAB = National Materials Advisory Board	TSC = thermal stress cracking
	UL = Underwriters Laboratories
	UV = ultraviolet
	WVT = water vapor transmission
	YI = yellowness index

CHAPTER 1 INTRODUCTION

An overview of plastic materials, including their classification and an insight into their polymer structure, and a review of material properties and American Society for Testing and Materials standards for testing are presented. A brief discussion of environmental factors and their influence on properties is included.

1-1 PURPOSE

This handbook provides a review of the material properties of plastics and their applicability to Army engineering design activities. The coverage is intended for those not familiar with plastics technology so they may learn more about the behavior of plastic material.

1-2 HANDBOOK OVERVIEW

This handbook provides a review of basic plastic material properties as they pertain to the design of components. The first chapter contains an introduction to plastic material properties and a brief review of plastic materials, their classification, and general behavior.

The second chapter contains a synopsis description of the design process for plastics. This information was included for those engaged in plastic design to emphasize their relationship with plastics technologists and how integrated product design will lead to maximizing materials use.

The remaining chapters discuss the material properties useful in design. These presentations are included to provide understanding of the numerous tests and material characteristics so widely used in the plastics industry and their significance in application development.

The properties discussed in this handbook are directed at moldable plastics. Although the concepts are related to films, composites, cellular, and other forms of plastics, the characterization of properties for these other forms is considered an extension of the approach described in this handbook. Test methods, specimen geometry, and property characterization differ depending on the form of the plastic.

A glossary has also been incorporated. It contains terms pertinent to plastics, material properties, and engineering design.

The users of this handbook will benefit by gaining a better understanding of plastics, their diversity, advantages, limitations, and most of all, those properties pertinent to engineering design. The handbook will provide a broad insight into considerations that must be given to plastics properties in the development of applications.

1-3 PLASTIC MATERIALS

Plastics are a class of materials having a broad range of characteristics that makes them competitive with the traditional metal, ceramic, and wood products. The advantages of plastics result from their unique, non-metallic features and the fact that they can be inexpensively mass-produced. Also plastics offer the product designer a wide range of properties and processing methods that allows innovative product development.

Like elastomers (rubbers) and fibers, plastics are broadly defined as polymers (Ref. 1). They are high molecular weight compounds formed by the linking of many (poly-) individual organic units called monomers (-mers) into long chains called polymers. This joining of varied organic molecules into long chains produces the many plastics available. Plastics are distinctive because they lack the extensibility of elastomers and the higher strength of fibers. Because their mechanical properties generally are between those of elastomers and fibers, plastics form a third group.

As a result of the manner in which plastics are formed, they are classified into two groups: thermoplastics and thermosets. Each group has certain structural characteristics that result in unique performance characteristics. This classification of plastics is further discussed in par. 1-3.1 and is followed by a brief discussion of the importance of the polymer structure.

1-3.1 CLASSIFICATION OF PLASTICS

As stated, plastics are broadly classified as either thermoplastic or thermosetting materials (Ref. 2). A list of typical plastics classified by type is contained in Table 1-1. Although this list is not all-inclusive, it is obvious that there are generally more thermoplastic than thermosetting types. Each type is distinctly different in its inherent behavior, as is each plastic listed under its respective type. Both types are polymers, however, which like most materials are solid at room temperature.

Upon heating all thermoplastics begin to soften, eventually reach a melting point, and become viscous liquids. Allowing a thermoplastic to cool below its melting point causes it to return to the solid state.

TABLE 1-1. LIST OF PLASTICS

THERMOPLASTICS	THERMOSETS
Acrylonitrile butadiene styrene	Diallyl phthalate
Cellulose acetate	Epoxy
Cellulose acetate butyrate	Melamine formaldehyde
Chlorinated trifluoroethylene	Phenol formaldehyde (phenolic)
Polyacetal	Polyester
Polyamide (nylon)	Urea formaldehyde
Polybutylene terephthalate	
Polycarbonate	
Polyethylene	
Polyimide	
Polymethylmethacrylate	
Polypropylene	
Polystyrene	
Polysulfone	
Polytetrafluoroethylene	
Polyvinyl chloride	

Thermoplastics therefore undergo a physical change during the heating and cooling cycles, which theoretically can be repeated indefinitely.

Thermosets are polymers that become fixed into permanent shape when heated. When the thermoset, in either an original liquid or solid form, is heated to a curing temperature, a chemical reaction occurs that causes the molecules to join or "cross-link" to form an infusible material. After this cross-linking or curing process, the thermoset cannot be returned to its original state; it remains a solid.

This inherent physical difference between thermoplastics and thermosets, coupled with the basic chemical structure, has resulted in the broad variation in the properties of plastics. Continued research in molecular structures has enabled polymer scientists to design and synthesize new polymers. Also the technologies available for processing plastics influence material development, i.e., various forms, e.g., film and foam, of each material are possible. These technologies are continually expanding and lead to greater capabilities for plastic materials in design applications.

Current material technology includes the use of additives to improve processing or end use characteristics. Such additives include lubricants, stabilizers, colorants, fillers, reinforcements, and plasticizers—all of which have varying effects on properties—and thereby further increase the number of materials available for design. Composite materials are an excellent example of this technology. The use of liquid thermosetting plastics

(primarily epoxy resins) in conjunction with continuous, high-strength fibers results in materials that are superior to metals on a strength-to-weight basis. Composite technology has become a major part of the plastics industry.

The term "plastics" embraces many materials, and each material has a unique set of properties. Plastics should not be viewed as replacements for metals, but rather as a distinct group of materials having inherent advantages and disadvantages. The material selection phase of design is based on a keen awareness of material characteristics, process technology, test methods, and conditions from which properties are derived.

The term "resin", which is used synonymously with "plastic" or "polymer", refers to any thermoplastic- or thermosetting-type plastic existing in either the solid or liquid state before processing.

Special terminology for moldable-type materials, such as "engineering plastics" and "structural foam", has been used to distinguish certain plastics. Such terms probably originated to characterize materials substituted for metals in certain structural applications. Although these terms imply exceptional characteristics, there are other materials not classified as such that also have engineering applications. Thus materials should not be classified on the basis of these terms.

As polymer process technology progresses, the application of thermoplastics and thermosets has become less distinct—e.g., the injection molding process once used solely for thermoplastics is now used also for thermosets. Thermoplastic resins can now be cross-linked during or after the manufacturing process. Although the distinction between these classes of materials is still valid, a lack of understanding of new materials technology may limit their usefulness in development of military applications.

1-3.2 POLYMER STRUCTURE

Polymers, unlike metals, are not orderly crystal structures that extend in all directions. Polymers are long chain molecules entangled into random shapes and having discrete lengths. The resultant molecular configuration depends on the chemical composition and how the molecules are arranged during their manufacture and/or processing. Although this area is mainly addressed by polymer chemists, the polymer structure is commonly used by plastics specialists to understand behavior better and to predict response.

For the designer not having a background in plastics, the mere recognition that these chemical and structural differences exist should aid in development of plastic applications; however, a greater working knowledge of molecular parameters would be a major asset. The paragraphs that follow describe a few fundamental terms that will provide a better understanding of material property response as described in the subsequent chapters.

The compositions (Ref. 1) of polymers center on a main chain of carbon-to-carbon atoms, to which elements or functional groups of hydrogen, oxygen, nitrogen, and sulfur are attached—just to mention a few. The polymer chains, which are in intimate contact, are bonded together by intermolecular forces. The arrangement of either the simple or complex chemical forms results in the varied, inherent material characteristics. Characteristics such as melting point, chemical stability, strength, and stiffness are directly related to structural configuration.

Polymers may be produced with a single (homo-) kind of monomeric unit or with two (co-) kinds and are therefore referred to as homopolymers or copolymers, respectively. Homopolymer characteristics are derived from the inherent molecular structure, whereas copolymers result in a variety of properties, which depends upon the type and proportion of molecular units. How copolymers are blended, either randomly or with a regular pattern, also influences their performance. Copolymers have resulted in many unique commercial polymers. Also polymers with three types of monomeric units are referred to as terpolymers.

Plastics are derived from the polymerization process and are defined in terms of molecular weight—a measure of chain lengths. The chain lengths will vary and are measured in terms of the “number” or “weight average” molecular weight. Molecular weight and its distribution have a direct bearing on the behavior of a plastic, particularly on its strength and toughness.

Polymer chains generally conform to molecular shapes referred to as linear or branched. Linear polymers, because of their relatively long, narrow configuration, may be extended readily to enable chains to align themselves. Branched polymers, however, because they contain short chains attached to the main chain, may vary in length and hinder alignment of the long chains. This basic difference influences plastic response. Most of the theoretical investigations of polymers are based on linear structures.

For thermoplastic-type materials, the alignment and packing of polymer chains lead to a molecular characteristic referred to as crystallinity. Highly crystalline polymers are not completely crystalline; they have some amorphous regions. Plastics also exist in semicrystalline form; they also can be completely amorphous. Crystallinity is a function of the polymer structure and its thermal history and at times is influenced by the processing method.

The terminology discussed in the preceding paragraphs is generally associated with thermoplastic materials. This association is the result of their inherent polymer structure and its capability for modification and variation compared to thermosets. When a polymer is cross-linked, as are the thermosetting plastics, the resultant structure is a three-dimensional network of interlocked chains. The char-

acteristics are distinctly different from those of thermoplastic polymers in that the molecules are less mobile due to the cross-linking. Cross-linked plastics are insoluble materials having high rigidity and low extensibility.

The plastics specialist is tasked to relate performance properties to the molecular structure in order to understand the behavior of materials better. The designer always benefits from working with these specialists.

1-4 MATERIAL PROPERTIES

The material properties discussed in this handbook include those considered useful in engineering design, particularly for the material selection process. Typically, much of the data generated at present is in the form of “single point” values, which do not adequately characterize material performance (Ref. 3) for design. The intent of this handbook is to describe each property, to suggest how the data should be presented, and to emphasize its engineering significance.

This handbook will not discuss design properties, i.e., those properties that are a function of specific applications such as bearings and gears, nor will the handbook consider design data related to shape or unique engineering environments such as outer space.

This handbook is not intended to suggest new test methods but to discuss data formats developed within the existing framework of the American Society for Testing and Materials (ASTM). The handbook provides encouragement to product developers to promote the standardization, uniformity, and completeness of material property data.

The handbook is intended to provide the most basic viewpoint on material properties and their use, which is necessary for those designers not skilled in plastics. This purpose necessitates that data be basic, practical, understandable, and adaptable to a wide range of applications.

In pars. 1-4.1 and 1-4.2 the military relevancy of plastic material properties, as classified by the ASTM, is discussed. The current trend within the Government is toward greater use of commercial specifications and standards. This view has been considered in this handbook.

1-4.1 CLASSIFICATION

For the evaluation of materials ASTM provides standards that are published yearly in a number of volumes. The ASTM standards for polymers are contained in four volumes. Each standard for testing has been developed for specific purposes and is described in detail. The test method standards contain the procedures for both testing and recording of test data.

The plastic test methods of interest in this handbook are listed in Part 35 of the *Annual Book of ASTM Standards* (Ref. 4). This list addresses testing those properties generally reported in trade journals and

material suppliers' literature for moldable-type plastics. Test methods contained in other ASTM books or parts that have been developed for film, cellular structures, and reinforced plastics are not discussed.

The Government equivalent of ASTM Part 35 is Federal Test Method Standard No. 406A. However, most of the test methods in this specification have been cancelled and have been superseded by their ASTM equivalents. The ASTM test methods are periodically revised to reflect current industrial practice; therefore, the test methods discussed in this handbook may vary subsequent to the publication date referenced.

ASTM test methods may be classified in two groups: (1) those used for research and development and (2) those used for quality control. This grouping is based on the scope or significance as described in each test method.

The category of research and development includes methods that evaluate material response for use in product applications and those that characterize inherent material behavior. Characterization as delineated in the standards includes evaluating changes in structure as a function of polymer modification processing or environmental factors.

Test methods for quality control include those useful for material identification, material flow, shrinkage determination, in-process evaluation, and product acceptance. Unfortunately, many of these quality-control-oriented methods are inappropriately used for material selection. Property data generated for research and development purposes can be very useful in quality control, but the reverse is not generally true. Also processing and quality control data are not useful in the design process, a statement reiterated in a number of ASTM specifications. The proliferation of quality-control-type data is not only misleading users but also is diverting energy and funds that could otherwise be applied to the generation of more effective material characterization data. User knowledge and understanding of properties and their significance can aid in redirecting efforts to the benefit of the entire design community.

Material properties are based primarily on "coupon" specimens and thus are limited in usefulness because most applications involve complex shapes and combined loading. Unless the test mode and the environment are identical to end use conditions, the resulting data cannot be used directly in design. Nevertheless, basic property data are essential for (1) predicting design performance based on elemental analysis, (2) comparing materials, and (3) evaluating the influence of environments. The basic laboratory data form the datum level from which all other material evaluations and assessments are developed.

The material properties discussed in this handbook consider the practices generally followed in the commercial sector because the plastics industry is responsible for most data generation. Because plastics vary broadly in

composition, data must be described in terms of the specific material under test. This description is best accomplished by associating data with a "trade designation", the identifier uniquely applied to a composition. These designations generally are cataloged in marketing and sales literature.

The specimen configuration and its fabrication method influence properties; therefore they require detailed descriptions. Table 1-2 contains the parameters that should accompany each set of material property data.

This handbook will restrict its coverage to those properties that are pertinent to material characterization investigations conducted during research and development, i.e., those relevant to the evaluation of material behavior. These properties have been divided into groups by subject area: mechanical, thermal, electrical, optical, physical, and permanence. These categories conform to those developed by ASTM as listed in Ref. 4.

1-4.2 MILITARY RELEVANCE

Development of military applications is performed in a manner comparable to that of industry. Differences, however, result from (1) the greater reliability required to assure performance under peacetime and critical wartime conditions, (2) the more severe environmental conditions that prevail for military hardware, and (3) the longer useful life for military hardware required in many systems. These differences dictate that more careful scrutiny is necessary in the application of all materials. The data requirements for materials in military applications are obviously related to their military end use, which necessitates that material testing be directed at military interest as well as industry. Unfortunately, most testing performed by industry may satisfy its own requirements but not those of the military. As a result, the design process for Army hardware is handicapped by the lack of adequate property data. Proper material selection demands comprehensive technical data to enable response prediction throughout the life of the hardware. Because of this lack of data, the response must be predicted by a "best guess" and/or costly, time-consuming testing and then verification by trial and error.

Army designers engaged in reviewing plastics will also encounter the results of a plastics technology expanded by, the ever-increasing number of plastics. The number of commercially available materials competing for the marketplace becomes overwhelming. Therefore, the material selection process demands an effective means of comparison. Unfortunately, inadequate data remain a major problem and inhibit effective product development.

One of the purposes of this handbook is the elucidation of basic properties of plastics significant in Army design; consequently, the handbook suggests that users promote the concepts presented to enhance the use of plastics.

TABLE 1-2. SPECIMEN IDENTIFICATION FOR TESTING

Polymer Name	The generic name given to the plastic as described in ASTM D883 or ASTM D1600 (Examples: polyamide, polystyrene, and epoxy).
Trade Designation	The specific designation given to a material by the supplier that uniquely identifies the grade and composition of material and usually includes a trade name and an alphanumeric designation. This designation should be directly associated with the test data.
Material Supplier	The company that manufactures and/or markets a specific material uniquely identified by an associated trade designation.
Fabrication Method	The method by which the test specimens were prepared (injection, compression, transfer, blow molding, etc.) including secondary operations such as stamped and machined and specific processing parameters when pertinent to the performance data. Specimens for test should be fabricated using the primary process for which the material was developed.
Date of Fabrication	The month and year the material was formed into the specimen configuration for test purposes.
Type of Specimen	A description of the specimen by its physical shape (disk, bar, rectangular, etc.) or intended use (tensile, flexure, etc.). The associated ASTM designation shall be used where appropriate (Example: Tensile bar, Type I, ASTM D638).
Dimensions of Specimen	The dimensions (length, width, diameter, and thickness) that define the specimen size according to that suggested in appropriate test methods.
Conditioning of Specimen	The treatment of the specimen preceding exposure in the intended test environment. Conditioning should conform to ASTM D618, Procedure A (23C/50RH/40H), where appropriate. Also refers to pretest treatment such as annealing, moisture conditioning, or other special conditioning procedures normally performed in a production environment for the material being evaluated.

1-5 ENVIRONMENTAL FACTORS

If any one design factor could be regarded as most critical to the performance of a product, it would have to be its environment. The influence of the environment on plastic materials represents an extremely important aspect of design because the useful life of such materials may be seriously affected. Deterioration or failure of a component can be very detrimental to military operations. Environmental considerations also result in higher costs for design and production control and generally create an additional maintenance burden.

The major environmental factors pertaining to Army materiel are divided into two groups, natural and induced, as outlined in Tables 1-3 and 1-4. These factors are thoroughly described in the Army Engineering Design Handbooks entitled "Environmental Series" (Refs. 5-8). This four-part series provides the most comprehensive review of worldwide environmental conditions as applied to Army materiel. The series describes the environment that would be encountered during the life of an item in the geographical area of interest.

The deterioration of material is sometimes accepted as natural and inevitable; the rusting of metals and cracking of rubbers are typical examples. Such deterioration can be avoided, however, through the proper selection of materials or by providing appropriate protection. There-

**TABLE 1-3
NATURAL ENVIRONMENTAL FACTORS**

Terrain
Temperature
Humidity
Solar radiation
Rain
Solid precipitation
Fog and whiteout
Wind
Salt, salt fog, and salt water
Ozone
Macrobiological organisms
Microbiological organisms

**TABLE 1-4
INDUCED ENVIRONMENTAL FACTORS**

Atmospheric pollutants
Sand and dust
Vibration
Acceleration
Acoustics
Electromagnetic radiation
Nuclear radiation

fore, the design engineer must first define the environmental conditions and then carefully scrutinize the materials available for use. Next the environmental factors must be evaluated in conjunction with the functional or operational requirements in order to assure desired product performance.

Temperature, humidity, solar radiation, salt, micro-organisms, atmospheric pollutants, and shock, etc., exert enormous influence on plastic materials. Combined effects—e.g., temperature and shock and/or temperature and humidity—are even more severe, especially when coupled with the operational requirements. Therefore, material property data as influenced by these factors are essential in all military developments.

Realistically, testing of plastics that considers all the environmental factors and the multiplicity of combined effects is not practical. The factors that are the most critical are temperature, humidity, shock, and solar radiation. Minimally, these factors should be evaluated on a standard basis for all materials.

An environmental test useful in evaluating performance is outdoor exposure, commonly referred to as weathering. It evaluates the influence of many environmental factors on a diurnal basis. Artificial indoor weathering tests, termed accelerated tests, are also used to evaluate environmental effects; however, these results do not always duplicate actual weathering.

The material properties described in this handbook do not consider all the environments listed in Tables I-3 and I-4. Temperature and humidity, the most significant environmental factors, have been included throughout. Where appropriate, other specific environmental factors

have been considered. Each chapter also contains a discussion of the environmental effects for each category of material property.

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CHAPTER 2

DESIGNING FOR PLASTICS

Because they differ in behavior from conventional materials of construction, plastics require greater scrutiny during the design process. An integrated plastic product design process is defined and its elements discussed in detail. Also included is a review of process technology for plastics. The product assurance considerations and testing technology necessary to achieve effective designs are also discussed.

2-1 INTRODUCTION

Conventional structural materials—metals, concrete, wood, and glass—are used successfully because of their well-known advantages and disadvantages (Ref. 1). Rarely are they used in inappropriate applications. Although service failures of these materials do occur, they are usually caused by (1) manufacturing errors or defects, (2) exposure to unforeseen conditions, or (3) inadequate maintenance.

The situation for plastics, however, is somewhat different. Plastics are relatively new; therefore, many designers are not generally familiar with the subtle differences among plastics—a fact that may lead to improper design. Plastics represent a broader spectrum of materials (And more variations are being produced each year.) and are very complex in their behavior. Also, because plastics are not as well defined in an engineering sense, they must be selected very systematically, i.e., adherence to a formal design process is important.

The design process discussed in this chapter considers the basic, or traditional, approach to product development, i.e., design, manufacture, and test. A review of each of these broad areas is provided, with emphasis on the interrelationships among the technologies for these three areas. This emphasis, which considers the procedural elements that experience has demonstrated to be necessary for effective plastic use, has been described as an integrated plastic product design process.

In the past, the design of all products was less sophisticated because it was based on the use of elementary analytical techniques that used basic mechanical and physical properties. Today, however, engineering requirements are more complex (Refs. 2 and 3) and require more comprehensive analysis and materials property data previously considered unnecessary. Unfortunately for plastics, the testing and reporting of properties have followed the traditional practices followed for metals. Although basic properties can still be used effectively for metals, they pose serious shortcomings in their use for plastics. Plastics technology today demands credible design procedures and data for all engineering materials.

2-2 INTEGRATED PLASTIC PRODUCT DESIGN

2-2.1 DEFINITION

The term “integrated plastic product design” emphasizes the need to integrate the areas of product design, process technology, and testing for plastics. Integration includes consultation with various specialists to assure that (1) the most effective materials and processes are incorporated in the design (2) processing limitations and variables have been identified, and (3) a testing procedure for assuring product quality has been developed.

Within the Army the concept of integrated design is not new. Regulations have required participation by specialists in production, product assurance, maintenance, packaging, materials, and human factors engineering. This concept is applied on a system basis—missile system, vehicle, telephone handset, or artillery projectile—to assure compliance with the overall requirements. The concept of integrated plastic product design also applies more fundamentally to the design of basic components and specifically to the material and its role in meeting product requirements. Material engineering specialists are the focal point of effective material use.

Basically, the design of a product originates with delineation of the overall requirements, the development of a concept, and a product description in the form of a sketch or drawing. Product design finalization is the demonstration of acceptability and the result of considering the many factors that lead to manufacture.

Design, in another sense, considers the elements of function, cost, and aesthetics. The priority, or order of consideration, depends on the product and its intended use. Engineering design, as practiced within the Army, considers function to be primary and cost, secondary; aesthetics is rarely emphasized.

Function can be broadly defined as what the product must do, considering all operational and environmental conditions. Designing for function implies that the performance goals can be achieved. Although cost is considered to be secondary to function, design tradeoffs are made to maximize the operational aspects within cost restraints.

The functional requirements for much of the Army hardware are unique because hardware may remain in stockpile storage for 10 or more years, and it must perform reliably when committed to use. Functional performance becomes paramount because a military objective is involved and the lives of personnel are at stake.

The cost of hardware and/or components generally consists of the basic material cost and the cost to produce the item. Costs may vary widely, depending on which material and/or process is selected; therefore a basic understanding of both material and process technology is necessary. Army considerations also include the need to minimize operation and supports costs because operation, maintenance, and/or retrofit can be extremely expensive.

Aesthetics, or user appeal, plays a minor role in Army applications compared to its role in the industrial sector. Within the military aesthetics takes on the role of functional requirements. Aesthetic features such as color, surface finish, and decoration—which are widely used in industry for “sale appeal”—are functional requirements within the military. For example, color is used for camouflage, for coding purposes, and/or to provide a dull surface finish that will prevent reflection. Decorating methods usually are employed only to denote system parameters or identification.

Product appearance in military applications conforms to the design philosophy of “form follows function”. Form is governed by factors, such as ballistic shape (an aerodynamic requirement) or configuration to minimize bulk or to meet human factor requirements.

Thus design within the Army primarily focuses on achieving the functional objectives at minimal cost, and this approach is inherent in the integrated plastic product design concept.

2-2.2 DESIGNING FOR FUNCTION

The complexity of plastic materials and their broad use, as discussed in Chapter 1, “Introduction”, necessitate a systematic approach to design. Five basic steps have developed:

1. Establish design requirements.
2. Develop initial product design.
3. Select candidate materials.
4. Test production prototype.
5. Establish final design.

Following these key steps in sequence is very important. The design procedure may be described differently by others (Refs. 4 and 5), but all descriptions have the same end result. Plastic material and process technologies must be continuously considered in each step. The design process can be relatively simple when a design precedent has been established, or it can be complex when a new or unique development is begun.

The steps in design are also iterative; after test and evaluation, the initial design or material may require a change. This process is repeated until a successful product is achieved.

Each step in the functional design process is described in the subsequent paragraphs. Because behavioral differences between plastics and metals are not self-evident and each requires a different perspective on performance properties, greater emphasis is placed on the material selection phase. As previously indicated, properties and performance relationships require greater scrutiny for plastics than they do for metals.

2-2.2.1 Design Requirements

The requirements for a product depend upon its end use. They define what the item must do and what environmental conditions it must tolerate and must include economic factors, production requirements, and special features.

Within the Army an initial description of performance or system requirement is prepared. This document contains the overall requirements that the projectile, helicopter, rifle, communication equipment, or vehicle must meet. Also the system requirement generally will detail the operational and atmospheric environments. Although general in nature, the requirements form the basis upon which overall performance will be evaluated.

Generally, the requirements for a component or part are developed during the design concept stage from system requirements. The intent is to specify quantitatively, and as completely as is practical, the essential part functions and the environments to be encountered. To distinguish between mandatory requirements and those that are only desirable is also important because the resulting part design and material usually are arrived at through many design tradeoffs.

To derive these requirements, a series of factors, as shown in Table 2-1, normally are considered. The design considerations are described in the form of qualitative or quantitative statements, which begin to categorize the design approach and material selection. Key considerations for plastics are strength requirements, environmental factors, and production requirements.

The factors listed in Table 2-1 are by no means all-inclusive. Presumably all parameters can be specified for each part, but this listing is not always possible (Ref. 4). At this early stage of design, the product configuration may not have been determined. It is important that the designer consult with material specialists early in the initial product design and until all requirements are specified and documented. The final list of design requirements must be expressed in terms of material properties to facilitate a suitable selection.

**TABLE 2-1. CONSIDERATIONS
IN ESTABLISHING DESIGN
REQUIREMENTS**

1. Configuration:
 - a. Basic use
 - b. Size and shape
 - c. Weight
2. Structural:
 - a. Static, dynamic, or cyclic forces
 - b. Load magnitudes and durations
 - c. Strength and stiffness
3. Nonstructural:
 - a. Thermal, electrical, optical, and physical properties
 - b. Color, surface finish, and identification
 - c. Fire resistance and materials compatibility
4. Environment:
 - a. Temperature and humidity ranges in storage and use
 - b. Weathering and water resistance
 - c. Chemical and biological resistance
 - d. Service life and degradation characteristics
4. Production and Cost:
 - a. Total quantities and production rate
 - b. Secondary operations and special features
 - c. Cost restrictions
 - d. Standardization

2-2.2.2 Initial Product Design

After the concept for the item has been developed, design details must be generated. Initially, product design involves "design for configuration", which includes shapes, dimensions, and specific functional details. These parameters begin to establish the type of plastic to be considered and the basic fabrication process. This initial phase also includes preliminary analytical design, tolerances, space restrictions, weight requirements, and assembly with other plastic or metal components.

As the design evolves, additional requirements are generated that include allowable stress levels, deformation limits, thermal expansion requirements, compatibility requirements, stress-temperature-time relationships, electrical requirements, and others.

The design under consideration definitely benefits if the designer has detailed knowledge of material properties and how materials are used. When this is not the case, consultation with material specialists provides the necessary guidance. When the design requirements are defined in terms of material properties, specialists can begin to categorize and select the materials.

2-2.2.3 Material Selection

The material selection process for plastics is thought of as a laborious and nearly impossible task (Ref. 5), and for

the uninitiated, it is. There are hundreds of distinctly different materials that are the result of combining generic types, fillers, reinforcements, and manufacturing processes.

The use of plastics demands knowledge of behavioral factors of specific materials which include creep, temperature sensitivity, water absorption, dimensional stability, fatigue, toughness, chemical resistance, and stress crack resistance. It is for this reason that the selection process for plastics requires expertise in material technology. This expertise also includes process engineering and tooling. Consultation for material selection begins in the initial design stage and continues until the design is finalized.

Material selection is basically a two-step process. The first step is an initial screening (See par. 2-2.2.3.1.), and the second is the selection of candidate materials (See par. 2-2.2.3.2.). Both steps require a review of the part requirements and of the initial part design, which should be followed by discussions with project personnel about design options, potential materials, fabrication processes, and cost.

2-2.2.3.1 Initial Screening

The initial screening of materials is performed to categorize the types of plastics to be examined as possible candidates. This choice is based on inherent material properties not subject to enhancement by design. These go- or no-go-type requirements—which might include transparency, chemical resistance, or temperature resistance—immediately limit the types of materials to be considered. The list of materials may also be shortened by considering part shape and general strength requirements.

The initial screening should also consider producibility, which is the capability for ease of production. Limitations of the manufacturing process and its tooling include factors such as parting line, draft, thickness, tolerance, undercuts, inserts, and subsequent joining techniques. Such producibility factors are widely published and must be considered in the initial product design stage.

2-2.2.3.2 Candidate Selection

Choosing the right material is probably the most important decision to be made in an application (Ref. 6). If a material subsequently proves to be inadequate, reevaluation may be time-consuming and costly. The selection of candidate materials can range from simplified substitution based on well-established precedents to complex assessment of the full range of available plastics.

A key element in the selection process is the analysis of part design requirements and the translation of these into meaningful material property requirements. Whether simple or complex, the requirements must be described in terms of properties and the combined effects of environments—e.g., strength and impact as affected by temperatures, humidity, time, and/or chemical exposure. Candi-

date materials are selected by comparing their properties with the material property requirements developed for the part.

Some product designs are easily modified, e.g., strength and stiffness can be altered by a change in wall thickness. A change of this type can qualify a material that would otherwise be considered inappropriate. In the material selection stage it is important that consideration of design options be conducted to select the most effective material.

A problem faced in the selection of materials is the difficulty encountered by the uninitiated designer in assimilating the vast amount of available material property data without an understanding of the behavior of plastic materials.

This problem is made more difficult by the lack of fully characterized engineering property data for commercial plastics (Refs. 7 and 8). Most data are single-point data of questionable reliability rather than validated properties to include the interplay of multiple variables in graphical form. This lack of credible data often results in the requirement to perform additional material testing or trial-and-error product evaluation.

Structural data use lacks a good method to adapt the true performance properties of plastics to the design technology that has evolved around the theory of elasticity (Refs. 9 and 10). A fundamental understanding is required of the viscoelastic nature of plastics and what properties are useful in design.

If there are no material property data that relate directly to a part requirement, a qualitative judgment must be made and followed by testing to evaluate performance. An example of this approach is the prediction of the resistance to impact of a field telephone, i.e., a requirement that it withstand a 1.5-m (5-ft) drop at a specified low temperature. The analysis for the handset drop is extremely complex, if possible at all; therefore, an empirical, trial-and-error approach is the only approach available.

The result of this initial screening and selection process should be a list of candidate materials that includes the associated cost factors and that is worth pursuing in the prototype evaluation stage. Depending on the program requirements, additional review of the materials may be conducted to narrow further the list of plastics in an order of priority.

2-2.2.4 Prototype Evaluation

The prototype stage of a project provides the first opportunity to evaluate product performance. Prototype evaluation presupposes the fabrication of a part or product by the intended manufacturing process. Initially, the inclination is to prepare a prototype by machining or by another simplified model-making technique. This practice should, however, be avoided for detailed engineering tests. Parts manufactured by other than the intended

process can provide very misleading results because material properties are greatly influenced by the manufacturing process. If such an approach is used, allowance should be made in evaluating test results; the prototype part may be distinctly different from the production item.

Although it may be more costly to manufacture parts with production-type tooling, testing of these parts provides the most beneficial means of evaluation. Prototypes should also be representative of the final design with respect to the specific material used, the configuration chosen, and the use of special requirements, such as ultrasonic welding. It is essential, for instance, when testing colored parts for impact, to have the color incorporated because the presence of color additive may have a significant effect on impact resistance.

Testing of parts under actual conditions of use is the most effective form of evaluation. Although this form may not be practical because of cost or induced hazards in the event of failure, all performance requirements are encountered and a fairly complete assessment can be made. When end use testing is not practical, simulated service conditions should be employed. Tests may include temperature cycling, load cycling, electrical performance, environmental exposure, static and impact strength tests, and others—all performed under conditions subject to measurement and recording. To reiterate, it is extremely important at this point, i.e., prior to the production phase, to assure that the part and/or product performs as desired under all operational and environmental conditions.

Because testing for the service life of the item is generally impractical, accelerated testing can be used to evaluate performance. Such testing can be worthwhile if conducted by experienced, qualified personnel. It is advantageous to initiate long-term testing as early as possible and concurrently with accelerated tests and to continue it for an extended period of time.

Other valuable approaches to plastic part evaluation are "overtesting" and testing to failure. These approaches may include temperature cycling beyond the required limits, drop tests from greater heights and at lower temperatures, induced stresses until part failure, and other tests considered to be very severe. These tests establish the performance limits of the product and instill confidence in those using it.

In the final design stage, consideration normally is given to specifications for production. These specifications generally include raw material identification, part dimensions, tolerances, color, finish, and other pertinent appearance features. What is often needed, however, is an engineering test to assure product performance. Product assurance testing entails defining critical product requirements and the means of measurement, which may be the measurement of material properties or practical tests that will enable assessment of product quality. Generally,

these product performance procedures should be developed from the prototype testing stage.

A simple example is that of an equipment case requiring impact resistance. Following product acceptance from actual drop tests, a laboratory test (weight dropped onto the case) can be developed to establish acceptable limits that would be used as a production method of assuring product performance. The testing limits, however, must be closely coupled with actual drop test results.

Also the prototype provides the opportunity to assess the influence of manufacturing process variables on product performance. Plastic processes subject the material to rather severe physical conditions involving elevated temperature, high pressure, and high shear-flow rates. These conditions, coupled with variable cycle times, other machine variables, and postmolding procedures, can result in internal stresses that can lead to product failure. Knowledge of these variables and their influence on the product provides greater understanding of material and product performance. The evaluation of process variables can also be used to determine the effectiveness of the product assurance procedures intended to measure product integrity.

Although treated routinely, overall prototype testing can play a major role in characterizing material and product limits. The integration of both material and process technologies into the design process leads to greater product assurance of the final design.

2-2.2.5 Design Finalization

The completion of a design inevitably manifests itself in engineering drawings. They primarily detail dimensions and tolerance limits; materials; surface finish, color, and marking; and special requirements and features as needed for production control.

Design finalization should also include documentation of the entire integrated product design process, i.e., it should describe the requirements, the design, material selection, and product evaluation. An important part of the documentation is the detailing of requirements as they relate to product performance testing, i.e., the product and/or material requirements as they relate to actual part function. The engineering details described in a design finalization report can become the basis for specifications developed for product assurance and will provide technical details for future reference.

2-3 PROCESS TECHNOLOGY

A factor contributing to the growth of plastics use is the innovations made in process technology. Coupled with material developments, they have promoted many new uses of materials. For example, injection molding of thermosetting materials and the use of structural foams

formed from existing injection molding equipment have become commonplace. Technological changes demand that designers keep abreast of developments and extend traditional plastics thinking to the new techniques in order to capitalize on their potential for improved product performance and/or reduced costs.

The paragraphs that follow provide a brief synopsis of plastic processes and the interdependence of product design and material properties. They also present product assurance considerations as they apply to production hardware.

2-3.1 PROCESS CONSIDERATIONS IN DESIGN

The converting of plastic resins into end products is a highly specialized field encompassing a number of primary processes. Each process is virtually unique in its operation, its tooling, and product shape—all of which are pertinent to product design efforts (Ref. 10). The selection of any process must be done carefully on the basis of part geometry, the intended material, and cost.

Process technology also includes secondary operations that, in themselves, represent significant achievements to complement the basic processes. These secondary processes too are unique and must be carefully applied. Both the primary and secondary processes are described in the subparagraphs that follow to provide the reader with additional insight into plastic process technology, which is an important aspect of designing for plastics.

2-3.1.1 Plastic Process Methods

Of the many processes currently employed to manufacture plastics, the most important are listed in Table 2-2, and these account for most of the processing of plastics. Many of the low-volume processes—vacuum bag molding, filament winding, and vacuum forming—of Army interest have not been discussed in this handbook because property presentations differ because of their inherent structure and process techniques.

Reviewing Table 2-2 reveals that some plastic parts can be manufactured by more than one process, whereas others are limited to one process. Also certain materials and part design configurations dictate the process to be used, and certain processes dictate the materials. To ascertain the most amenable process, a thorough knowledge of all processes including their advantages, disadvantages, and limitations is highly desirable. Thus consultation with specialists in the field is essential to those lacking this familiarity.

The variables associated with each process play a major role in performance, as described in the paragraphs that follow.

TABLE 2-2. METHODS USED TO PROCESS PLASTICS

PROCESS METHOD	DESCRIPTION	REMARKS
Blow Molding	Shaping a thermoplastic material into a hollow form by forcing material into a closed mold by internal air pressure. Normally initiated with a form made by extrusion; it is now possible to injection mold the initial form.	High production rate process for manufacturer of hollow items such as bottles, tanks, and drums; uses relatively inexpensive molds
Casting	Forming a solid part by pouring a liquid resin into a mold and removing the part following curing or solidification	Practical for small production where inexpensive tooling is employed; primarily used for encapsulation of components or for parts having thick sections
Compression Molding	Principally used for thermoset parts formed by placing material into an open mold and curing the part by use of heat and pressure after the material is confined with a plunger	Principally for thermosetting materials of simple shapes having heavy cross sections, high impact fillers, or large deep-draw areas. Cycles are relatively slow, and finishing of parts is required.
Extrusion	A process for making continuous forms by forcing a thermoplastic material in the plastic state through an orifice or die. Thermosets are now somewhat adaptable to extrusion.	Limited to the continuous, low-cost production of rods, tubes, sheets, or other profile shapes; capable of extruding solid, foamed shapes
Injection Molding	A basic molding process wherein a heat-softened thermoplastic material is forced under pressure into a closed mold. Upon cooling and solidification, the part is ejected. Now widely used as a process method for thermosets and for thermoplastic forms	A major, high production rate process used for manufacture of intricate shapes. Process maintains good dimensional accuracy. Mold costs are relatively high.
Reaction Injection Molding	A process that involves the mixing of two liquid components, injecting the liquid stream into a closed mold at relatively low pressure, and removing the part following cure	A recently developed injection-molding-type process used for the manufacture of large, solid, or cellular parts. Low pressure and ambient temperature materials eliminate the need for expensive machinery.
Rotational Molding	The forming of a hollow part from thermoplastic resin within a closed mold by heating, rotating, and cooling the material for subsequent removal	Useful for manufacture of hollow forms with practically no limit to size and shape. Either rigid or flexible parts can be made with inexpensive tooling.
Thermoforming	The forming of thermoplastic sheet material into a three-dimensional shape by heat-softening the sheet and forcing it to conform to the shape of the mold by pressure or vacuum; followed by cooling	Limited to simple, three-dimensional shapes for signs, trays, cups, domes, and packaging. Tooling is relatively inexpensive.
Transfer Molding	A basic molding process for thermosets; part is formed by transferring the molding compound, which has been heated in a loading well, under pressure into a closed mold where curing takes place.	A process used exclusively for thermoset materials in the manufacture of intricate shapes and parts with fragile inserts. Process maintains good dimensional accuracy.

2-3.1.2 Process Variables

The manufacture of a plastic part usually subjects the material to varied conditions of temperature, pressure, and time during the basic forming process. These three primary process variables are important because they affect the performance of plastic parts. If processed improperly, plastics suffer dimensional instability, tend to warp, or possibly fail prematurely by stress cracking. Given these possibilities, designers may desire either to divorce themselves from plastic entirely or to institute excessively strict controls of the process conditions or variables. Neither of these choices, however, is the correct one.

Inherently, each process has a number of controllable variables. For example, the injection molding process contains approximately two dozen variables, which are presented in Table 2-3. Some of these have a very significant effect on material properties, whereas others have little or no effect. Regardless, it is impractical to prescribe a specification of each because specific situations may vary widely with molding presses, with the tooling design, and even the local molding environment.

Also any attempt by the buyer to define the process conditions in the manufacture of a part results in the buyer's having to accept all production quantities whether they are good or bad. In essence, the buyer is telling the manufacturer how to make the part and therefore is assuming all responsibility for nonperformance. This approach to procurement has been encountered in Army applications and has resulted in the Army's assuming responsibility for inferior production quantities.

The answer to this dilemma lies in understanding how process variables influence performance, evaluating their effects, and instituting quality assurance procedures. For instance, common practice in the trade is to minimize injection molding cycle times and thus increase the profit

margin so that appearance and dimensional requirements are met. The resultant part, however, may be under severe internal stress, and such parts are prone to dimensional change or failure at a later time. Therefore, during prototype evaluation, parts should be molded by using short cycle times and tested to determine the influence of such short times on performance. Such tests can show how variables will affect performance. When an in-process evaluation procedure can provide an adequate assessment of part quality, it can become part of the purchase specifications.

A necessary part of the process is its tooling. In the procurement of plastic parts, manufacture is accomplished according to an engineering drawing. Unless supplied by the buyer, the tooling design and associated manufacture are the responsibility of the producer. Because the tooling design has a significant effect on product performance, it is necessary to consider the implications.

As with machine variables, dictating what type of tooling and the parameters of size and shape places the onus of performance on the buyer. The most the buyer should do is to provide guidance as "suggested only". Again, it is important to understand and identify the effects of tooling on design performance and to establish appropriate product assurance parameters.

2-3.1.3 Secondary Process Operations

There are numerous types of secondary process operations that fall under the categories of finishing, joining, and decorating (Ref. 10). Many are quite useful in achieving design features not readily possible with other materials. The adaptability of these operations to design significantly aids the producibility of products. A very brief review of these operations follows.

2-3.1.3.1 Finishing

Finishing operations include degating, deflashing, and machining; some or all of which are required after the part has been fabricated. Although degating and deflashing are very simple procedures, machining plastics warrants greater attention. Techniques used to machine metals are generally applicable to plastics but must be modified for effective performance. Such modifications are necessary because plastics have lower stiffnesses, lower thermal conductivities, higher coefficients of thermal expansion, and lower softening points. Also each type of plastic has unique properties, and as a result, it can be assumed that each has different machining characteristics, which should be well-known before use of any plastic.

2-3.1.3.2 Joining

Generally, the joining of plastics is accomplished by mechanical methods, adhesive bonding, or welding. Each method requires unique design configurations, shape, and size; all of which must be considered early in product

TABLE 2-3
INJECTION MOLDING
PROCESS VARIABLES

MACHINE VARIABLES	RELATIVE VARIABLES
Barrel temperatures (three)	Material drying
Nozzle temperature	procedure
Injection pressure	Use of regrind
Injection speed	Nozzle design
Injection hold pressure	Feed system design
Injection hold time	Gate design
Dwell time (mold cooling)	Cooling channel design
Mold open time	Postmold part treatment
Shot size	
Cushion	
Screw revolutions per minute	
Back pressure	
Mold temperature	

development to assure effectiveness of the joint in prototype testing.

Mechanical means of joining plastics include screw fasteners, inserts, snap fits, hinge mechanisms, and staking; these methods may include the joining of plastics to plastics or plastics to metals. Because of the potential for thermally induced stress, joint design cannot be treated routinely.

Adhesives bonding is highly specialized. Adhesives fall into five basic groups: solvent cement, bodied adhesive, monomeric cement, elastomeric adhesives, and reactive adhesives. No one universal adhesive or cement exists that will bond all types of plastic materials. Also certain plastic materials preclude the use of adhesives because of their chemical makeup. Although it is a very cost-effective means of joining plastics, adhesive bonding requires much skill and know-how for effective use.

Welding processes for plastics are unique and include ultrasonic assembly, hot-gas welding, hot-wire welding, induction heating, spin welding, vibration welding, and heat sealing. Each process is an art in itself and employs specific design configurations for effective use.

These technologies for joining plastics are very extensive. They provide the designer with great latitude in product development to facilitate assembly, to incorporate unique features, and to reduce cost. Each process, however, demands the technical knowledge of specialists for its effective use.

2-3.1.3.3 Decorating

Whether applied for functional or aesthetic reasons, decorating is frequently required in the manufacture of any plastic part. The methods include painting, printing, coloring, metallizing, and hot stamping. Many of the basic molding processes are also adaptable to practical decorating with raised or lowered letters, two-color molding, and in-mold decorating. To meet product requirements, these secondary processes and their variations must be compatible with the material and the design and, therefore, require consultation with specialists in each area.

2-3.1.4 Design Interface

It is inherent in the design process to consider the primary and secondary methods to be used in the manufacture of the product. Because there are a number of processes and variables, knowledge of these skills would be beneficial. Also to assure producibility, i.e., to optimize manufacture along with appropriate quality control and product performance specifications, consultation with the appropriate groups is essential.

All participating groups should be advised early in the design process of the product requirements and the design concepts. Discussions should be continued throughout

the design process to identify the possible manufacturing methods, their variables, and their influence on the product. Design participation should also be continued through selection, prototype evaluation, and final design. This early involvement leads to more effective product development.

The extent of design participation is dependent on the product requirements. Critical components, those whose failure would affect safety and reliability, must be studied more carefully than others.

2-3.2 PRODUCT ASSURANCE CONSIDERATIONS

Production of Government hardware is based mainly on a technical data package (TDP). The TDP contains drawings and specifications that detail the acceptance criteria for each part and assembly. In essence, the TDP contains all product assurance considerations including material acceptance, quality control, and performance specifications. Emphasis is placed on the integrated design concept to develop more effective performance specifications.

2-3.2.1 Military Specifications and Standards

Quality provisions are frequently cited by reference to military specifications and standards, particularly for material acceptance and standard components. Application of these documents must be examined to assure that conformance to a specification(s) also results in compliance with performance requirements.

The Department of Defense (DoD) has directed that, whenever possible, military specifications be replaced by industry standards, i.e., voluntary consensus standards. These industry standards include ASTM, the Society of Automotive Engineers (SAE), and the American National Standards Institute (ANSI).

2-3.2.2 Quality Control

The term "quality control" is a general term used to imply the control of product quality through either product measurement or the control of a manufacturing process. As discussed in subpar. 2-3.1.2, control of the manufacturing process is not desired for military products. Within the Army product quality is maintained by use of the TDP. The TDP sets the general standards by which the product is accepted, and these standards include dimensions, tolerances, surface finish, color, and general workmanship. Such requirements, however, although a measure of acceptability, may not completely reflect the true quality of the item. For example, dimensional stability is not reflected unless the item is exposed to an elevated temperature as anticipated in use. Therefore, development of performance specifications as described in the next paragraph—is required.

2-3.2.3 Performance Specifications

Performance specifications are procedures developed to evaluate part performance, and they may be developed from the methods of testing used in prototype evaluation. For plastics these procedures are extremely important in order to assure that the production techniques employed do not hinder performance. Testing can be either destructive or nondestructive, may employ existing methods, or may incorporate methods uniquely suited to the product. Tests may be applied to individual components, subassemblies, or assemblies, as appropriate. Overall, performance specifications are the most meaningful form of product evaluation.

2-4 TESTING TECHNOLOGY

The technology of testing plastics encompasses a wide range of procedures from those used in sophisticated polymer research activities to simplified bench tests uniquely developed for a specific product type. Tests are performed to measure material characteristics or product performance. The three relevant areas of interest are testing of materials for properties, prototype testing, and production testing, as described in the paragraphs that follow.

2-4.1 TESTING FOR MATERIAL PROPERTIES

Material properties for plastics are derived primarily from test procedures developed by the American Society for Testing and Materials (ASTM). ASTM's only purpose is to provide a standardized method for property determination; therefore, the measurement of properties is performed independently by using ASTM methods. The ASTM methods (Ref. 11) are used to generate basic material property data by using simple, laboratory-type specimens. In most cases the data are not directly applicable to typical design configurations and thus must be used with caution.

For engineering design purposes most property data are produced by material suppliers and are reported in marketing brochures or engineering data handbooks. Because it is common industrial practice to report data that do not completely follow the prescribed ASTM reporting procedures, the available data are inadequate.

Data used to evaluate materials for design purposes must reflect the consideration of many variables, a feature that is lacking in published data (Ref. 8). Comprehensive testing is costly, but the lack of comprehensive data hinders the design process. This problem causes designers to resort to redundant and costly testing in order to select a suitable material.

ASTM methods allow the use of varied test specimen configurations and conditions of test. The resulting data, however, make it difficult to compare materials. To

improve the quality of data used for design, further standardization is necessary, i.e., certain test parameters should be further standardized. Table 2-4 lists those general parameters from which all test data should be developed.

The limitations of material property data for commercial plastics reflect current industry practices. To prevent misapplication, users must fully understand plastic property data and their limitations, as outlined in this handbook.

If data are inappropriate or lacking, the user is responsible for requesting engineering-type data in the form described in this handbook prior to the selection of the specific material for use. This practice aids in promoting the generation and standardization of appropriate data.

The production of data on material properties for complex or unusual environmental conditions may be beyond the capabilities of the material suppliers. In such cases, special, product-oriented tests must be performed by the users, and the reporting of such tests should conform to the concepts described in this handbook and should be documented accordingly.

The ASTM test procedures have provided for accommodating the International System of Units (SI) for data. The use of SI is required in the military to promote standardization of hardware.

2-4.2 PROTOTYPE TESTING

Testing of the prototype part, product, or system focuses on the evaluation of performance. The effort should include an overall test plan that considers all performance requirements and defines the objectives of each test. The prototype test stage also provides the designer the opportunity to consider design alternatives, e.g., materials and manufacturing processes.

Prototype testing of end-items should assess each component and its role in product performance. Those parts considered critical, i.e., whose failure would jeopardize overall performance, should be identified. Critical plastic parts require review to determine which characteristics and/or properties are important, how material and process variables will influence performance, and which test procedures should be incorporated to assure the desired quality. This assessment necessitates working with material and process specialists and sets the stage for product performance specifications for quality assurance.

Prototype parts should be subjected to accelerated-type tests, including elevated temperature (beyond design limits), temperature cycling, and temperature and humidity cycling. Strength and special impact tests that are beyond design limits but are directly related to desired properties are also useful. Chemical exposure tests also should be done to assess characteristics, such as molded-

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TABLE 2-4. COMMON TEST PARAMETERS

Test Method	The method used to define the preparation, conditioning, and testing of laboratory specimens. Testing should conform to ASTM methods whenever possible.
Temperature	The temperature of the specimen environment during the period of evaluation. All tests should be performed at the standard laboratory temperature of 23°C (73°F); thereafter, at the ASTM D618 standard low temperatures of -55°, -40°, -25°, and 0°C (-67°, -40°, -13°, and 32°F); and at the high temperatures of 50° and 70°C (122° and 158°F). Testing at lower or higher temperatures according to the limitations of the material or the test environment should be performed on an as-needed basis.
Relative Humidity	The relative humidity of the specimen environment during the period of test. Tests performed at the standard laboratory temperature of 23°C (73°) should contain the ASTM D618 standard relative humidity of 50%. Other relative humidity test conditions should be 10% and 90%. Testing done at higher to lower temperatures with no humidity control should be stated in the test conditions.
Test Conditions	Applies to unique test parameters or conditions not covered by the test standard
Date of Test	The month and year the test of the material was completed. This parameter assumes the property evaluated is determined immediately following the termination of the exposure period.
Number Tested	The number of specimens tested or number of tests conducted to obtain the specific technical data described.
Standard Deviation	The amount of variability or dispersion encountered in the measurement of properties as determined by the numerical expression contained in ASTM D1898
Comments	Any appropriate remarks pertaining to the test procedure or test data. Comments may include type of test equipment used, whether the data are corrected or uncorrected, and how the data were prepared.
Test Apparatus	The equipment used to perform the test. Data should include equipment manufactured and model number, as applicable.

in stresses, which are not evident from general appearance. In fact, any test that provides information about product quality should be performed because detected deficiencies can be more easily corrected at this stage of development.

2-4.3 PRODUCTION TESTING

Testing during production normally implies evaluation of the part or assembly throughout manufacture. Emphasis is on the control of part quality by meeting drawing requirements and performance specifications. Product assurance personnel are responsible for these written requirements and determine the method of

measurement, acceptable standards or limits, and the statistical basis of acceptance.

The quality of the part is a primary consideration from receipt of material to its assembly into the final configuration. Acceptance specifications and in-process storage requirements are of concern during this period. For plastics, consultations with material specialists identify areas of importance. The assessment of performance during prototype testing assists product assurance personnel in establishing acceptance requirements for production.

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CHAPTER 3

MECHANICAL PROPERTIES

The mechanical properties are introduced by a discussion of their time dependence, which describes the dependence of properties on the rate of loading and their relationship to design analysis. The constant load response and creep properties are reviewed in depth along with the associated stress relaxation characteristics. Plastic response to varied rates of loading is described in terms of stress-strain properties for tensile, compressive, and shear modes of loading. Also discussed are the impact and fatigue modes of loading and their relationship to stress-strain behavior.

3-0 LIST OF SYMBOLS

- B = bulk compressive modulus, Pa (psi)
- E = elastic modulus of elasticity in tension, Pa (psi)
- G = modulus of elasticity in shear, Pa (psi)
- μ = Poisson's ratio, dimensionless

3-1 INTRODUCTION

The term "mechanical properties" generally refers to the strength and rigidity characteristics of a material subjected to mechanical forces. Virtually all applications require some degree of mechanical or physical integrity; therefore, the mechanical properties are used as an initial measure of acceptability. However, they are needed primarily to predict performance, i.e., to assure that load-bearing materials do not fail by rupture or that products do not deform beyond the accepted limits.

For plastics, response to external loading is complex and requires a basic understanding of inherent behavior and the influence of environmental factors. This understanding provides the capability to make an intelligent choice of material. Mechanical properties, as defined in this chapter, are those that characterize the basic stress and deformation responses of plastics to tensile, compressive, and shear forces as influenced primarily by the time rate of loading and temperature.

The mechanical properties discussed in this chapter vary from those that are useful in design calculations to those that allow material comparisons. Each property is reviewed from an end use viewpoint and in consonance with test methods and data availability. As appropriate, polymer-related terms are introduced.

Most evaluations of materials are performed using simple test procedures because testing to conform to end use conditions is difficult and expensive. Also for engineering property data for plastics, tensile response has gained

more attention than compression and shear and remains the most widely reported result. Tensile response is reported in terms of deformation versus time and stress versus strain—quite familiar in engineering.

Prior to discussing plastic response, it is desirable to review the well-known stress-strain behavior of metals. In the design of metal structures, product analysis considers mechanical properties based on isotropic, crystalline materials having very predictable and reproducible behavior. The typical stress-strain behavior for three metals is illustrated in Fig. 3-1. Typically, structural steels exhibit a linear stress-strain behavior to the proportional limit and a nonlinear response thereafter. The proportional limit, elastic limit, yield point, and ultimate strength and/or rupture are all fairly predictable.

In structural design using steel, working stresses are generally based on applying a factor of safety to the yield point strength (Ref. 1). Response to working stresses well within the proportional limit enables good prediction of strain deformation because of the predictable elastic modulus of the material. These calculations are performed using constituted equations based on the classical theory of elasticity.

This simplified metals design procedure is possible for a number of reasons. The proportional and elastic limits, within which the working stresses lie, are relatively high in comparison to the yield stress. The sensitivity of strength and modulus to various rates of loading is negligible, with the exception of extreme dynamic conditions. The properties are also relatively insensitive to temperatures encountered in normal use. Although it has been recently recognized that the linearity of the modulus (Ref. 2) is limited, it has not been a problem because metal structures are usually overdesigned so that their bulk conceals any existing nonlinear relationships.

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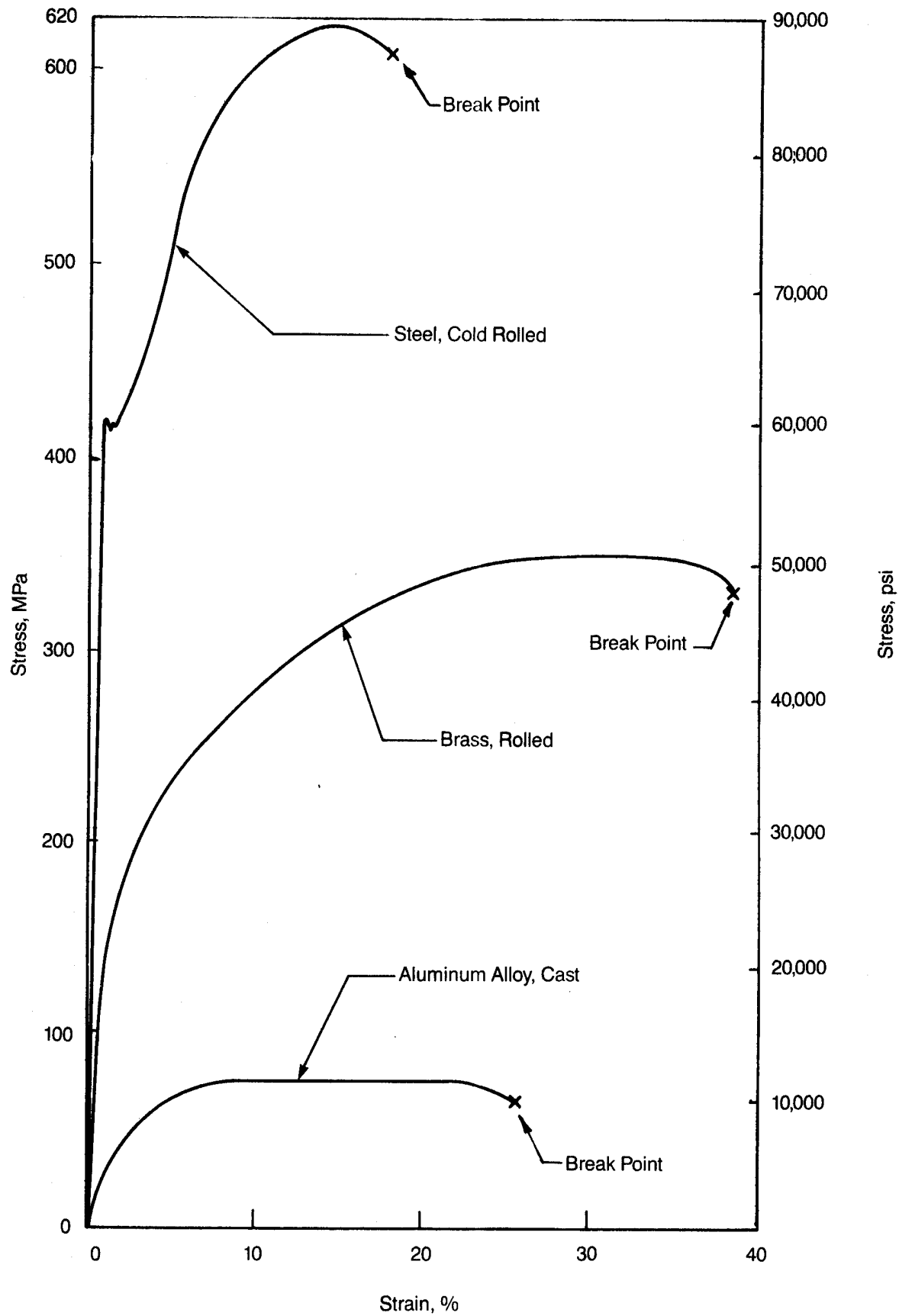


Figure 3-1. Tensile Stress vs Strain for Typical Metals

There are similarities between metal and plastic stress-strain behavior, but there are more differences that warrant attention. Typical stress-strain behavior for a variety of plastics is illustrated in Fig. 3-2. The ductile plastic behavior of polyethylene (Fig. 3-2) resembles that of a high-purity aluminum (Fig. 3-1), and certain plastic materials have curves similar to those of steel. Plastics, however, are inherently of lower strength and stiffness than metals. Because plastics are time and temperature dependent, the standard stress-strain curve alone is not suitable for comparing performance.

Metals are rate sensitive and temperature dependent, but plastics are more significantly affected by time rate of loading and temperature. Furthermore, as shown in Fig. 3-2, plastics do not have definable elastic and yield points as exhibited for steel. Plastics are viscoelastic materials that exhibit both a quasi-elastic response and a time-dependent viscous flow or creep. In spite of these differences, much of the simplified analysis performed for plastics uses the classical theory of elasticity.

The aspects of time-dependent behavior may not be familiar to all readers; therefore, discussion of both

constant load and rate loading is appropriate. This discussion is followed by a review of the engineering significance of load application in terms of creep, stress-strain, shear, impact, and fatigue properties.

3-2 TIME DEPENDENCE

The time-dependent behavior of plastics normally is characterized by the term viscoelasticity. It is determined in a creep experiment in which a weight or constant load is applied to a specimen. The initial response is an elastic deformation, which is secondary to the viscous deformation or flow (creep) with time. The level of load applied is well below that necessary to cause rupture and the time element is relatively long (months to years). Viscoelastic behavior generally is depicted by a strain deformation versus time curve.

This viscoelastic or creep behavior of plastics has been the subject of extensive investigations. Numerous texts (Refs. 3-7) are available to describe the theory, its limitations, and correlation with the experimental data.

The other type of time-dependent behavior is that in which a load or force is applied in a short, finite time

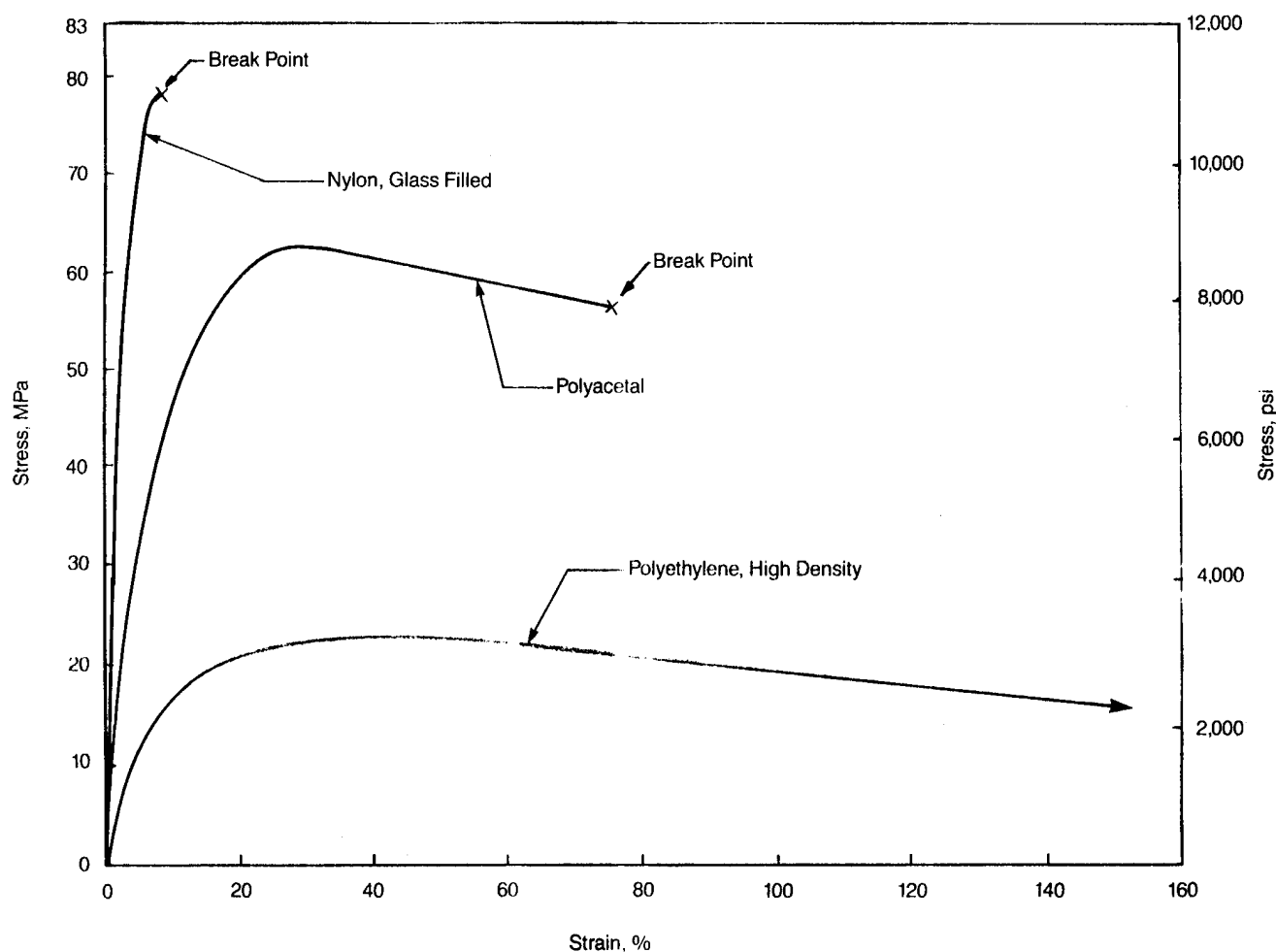


Figure 3-2. Tensile Stress vs Strain for Typical Plastics

period (minutes to seconds) and involves a measurable load rate or rate of straining. Material behavior, particularly the magnitude of load necessary to produce failure, is highly dependent on whether the rate of loading is low or high. Of particular interest is that rate of loading termed as high strain-rate loading. The response to various rates of loading, in these noncreep conditions, is best depicted by the stress-strain curve.

Unfortunately there is no industry standard that completely describes the high strain rate phenomenon. It is an area where researchers have not generated adequate approaches for design analysis or developed test methods and equipment to measure behavior adequately. Response to high-rate loading is complicated by the form of load induced, which includes behavior dealing with drop-type impact and cyclic loading.

To clarify time dependence in terms of strain rate loading, a schematic has been prepared and is shown in Fig. 3-3. It relates the strain rate to a qualitative categorization of load rate with an associated equipment type (Refs. 8 and 9).

In testing technology the rate of loading is described in machine terms of crosshead speed, in terms of the strain rate, or in reciprocal seconds (s^{-1}). The strain rate term has been used because it better describes the full range of load rates.

The low and high load rates have been categorized to reflect finite motion, whereas the very low rate has been categorized more appropriately as constant loading. As noted in Fig. 3-3, the high rate of loading has been extended to include very high and ultra high to accommodate the extremely fast levels of loading and methods of measurement.

3-2.1 CONSTANT LOAD

Response to a very low rate in the form of a constant load or weight is characterized by deformation at very small strain rates as shown in Fig. 3-3. The strain rate values are provided only as an indication of load rate in comparison to the other categories.

The response to a constant load is dependent on the inherent structure of the plastic. The polymeric chain-like molecules undergo a combined stretching and inter-molecular slippage, which results in elastic and viscous behavior, respectively. This behavior can be illustrated as a two-element or two-parameter model (Fig. 3-4(A) and (B)). The two elements are a spring (a mechanical analog of elastic strain) and a dashpot (a mechanical analog of viscous strain). The initial application of load or stress results in an instantaneous, ideal elastic- or Hookean-type extension of the spring. With time, additional linear deformation will occur that is manifested by the relatively slow movement of the dashpot. This behavior contrasts with metals, which are crystalline materials exhibiting primarily elastic, spring extension.

The theory of plastic behavior, however, is illustrated better by a four-parameter model (Fig. 3-4(C)) (Ref. 3). An initial constant load or stress results in an elastic strain deformation from the response of only the spring. The second response is a nonideal strain deformation in which the stress is no longer linearly proportional to the strain. This response is the result of deformation of the single dashpot and the parallel spring and dashpot combination. The initial elastic response is fully recoverable, the viscous behavior is nonrecoverable, and the combined elastic-viscous response is somewhat recoverable.

The theory developed for the four-parameter model assumes that the material is linearly viscoelastic. This assumption implies that the strains induced by the applied stress are linearly proportional to the stress as manifested in the short-term stress versus strain test for metals. For plastics the theory is applicable only at very small strains because plastic response is, for the most part, nonlinear. Thus the theory is not valid for most practical material assessments and has limited use in predicting plastic response.

The four-parameter model is useful to illustrate creep behavior when the constant stress is removed, a condition called creep recovery. The model is also used to evaluate a response called stress relaxation, a situation wherein a

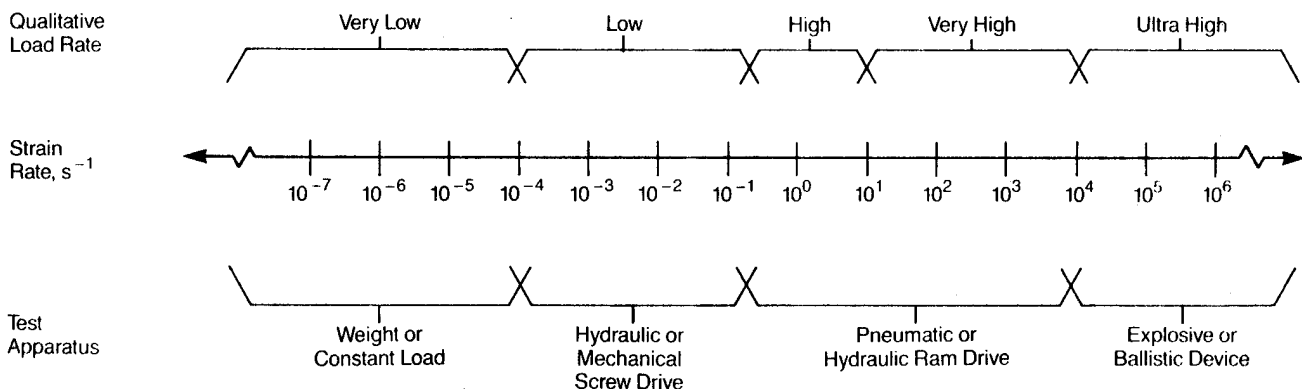


Figure 3-3. Strain Rate Loading

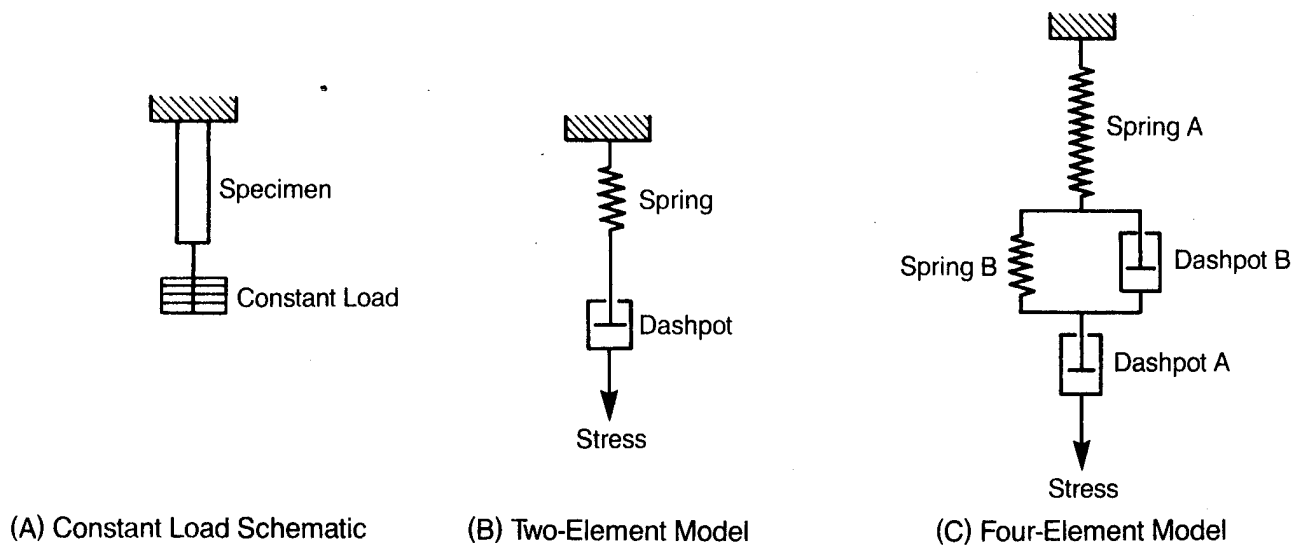


Figure 3-4. Viscoelastic Models

fixed deformation induces a stress that dissipates, or relaxes, with time. Another important viscoelastic response is stress rupture, which characterizes the short-time rupture of plastics subjected to relatively high stresses. All of these characteristics are discussed from a practical engineering point of view in the paragraphs that follow.

3-2.1.1 Creep, Creep Recovery, and Creep Rupture

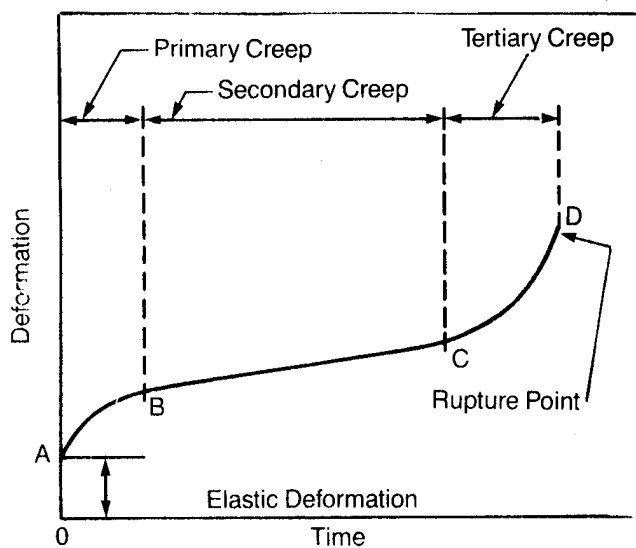
In addition to providing data for correlation with theoretical, constituted equations, the creep test provides very basic and useful engineering data. The test is performed by applying a load to a specimen and observing the deformation over time. The load is applied rapidly

and smoothly to avoid vibratory motion.

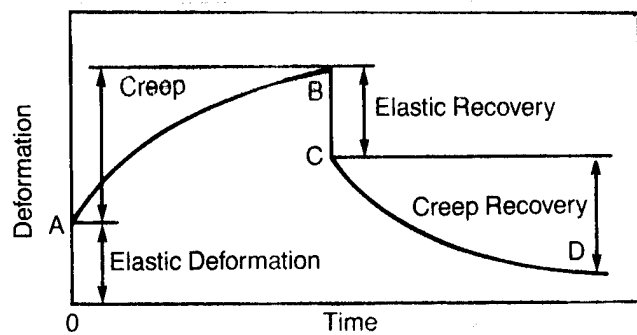
3-2.1.1.1 Creep

Creep measurements may be performed in tension, compression, pure shear, or torsion. For materials that are relatively stiff and brittle, creep measurements have been made in flexure. The flexure test, however, contains some inconsistencies and is not suggested for use.

The creep response, shown in Fig. 3-5(A), typically described in tension, is initially characterized by the elastic deformation (Fig. 3-5(A), point A) or strain at essentially zero time. A rapid rate of primary creep (Fig. 3-5(A), points A to B) then occurs and is followed by secondary creep at a slow and constant rate (Fig. 3-5(A), points B to C). If the load on the specimen is maintained indefinitely, tertiary creep will occur and result in rupture (Fig. 3-5(A), point D). Primary and secondary creep are characterized by a stretching of the material, whereas the tertiary stage encounters crazing or cracking. The observed responses from time zero conform to the four-parameter, viscoelastic model previously described.



(A) Creep Deformation



(B) Creep Recovery

Figure 3-5. Tensile Creep and Creep Recovery

3-2.1.1.2 Creep Recovery

If the applied load is removed at any point during the secondary creep period, the initial elastic deformation is immediately recovered (Fig. 3-5(B), point C). Thereafter, a decrease in deformation occurs, which is commonly referred to as creep recovery. Although the recovery is not complete (Fig. 3-5(B), point D), it is substantial. The portion of creep that is not recoverable results from the purely viscous response.

3-2.1.1.3 Creep Rupture

The creep behavior of plastics is highly dependent on the stress level (Fig. 3-6), i.e., the higher the stress, the

greater the creep, whereas for very low stresses the creep deformation is very small or nonexistent.

For very high stresses, i.e., those approaching the short-time tensile strength, failure will occur within a relatively short period of time. This failure mode is known as creep rupture. Several creep rupture points (Fig. 3-6, points A, B, and C) are used to plot a creep rupture envelope, which indicates the stress levels to avoid to prevent premature product failure.

Theoretically, if the typical creep deformation (Fig. 3-6, points D and E) experiment were continued indefinitely, a point would be reached at which fracture might occur. (The time involved is a few years to many years.)

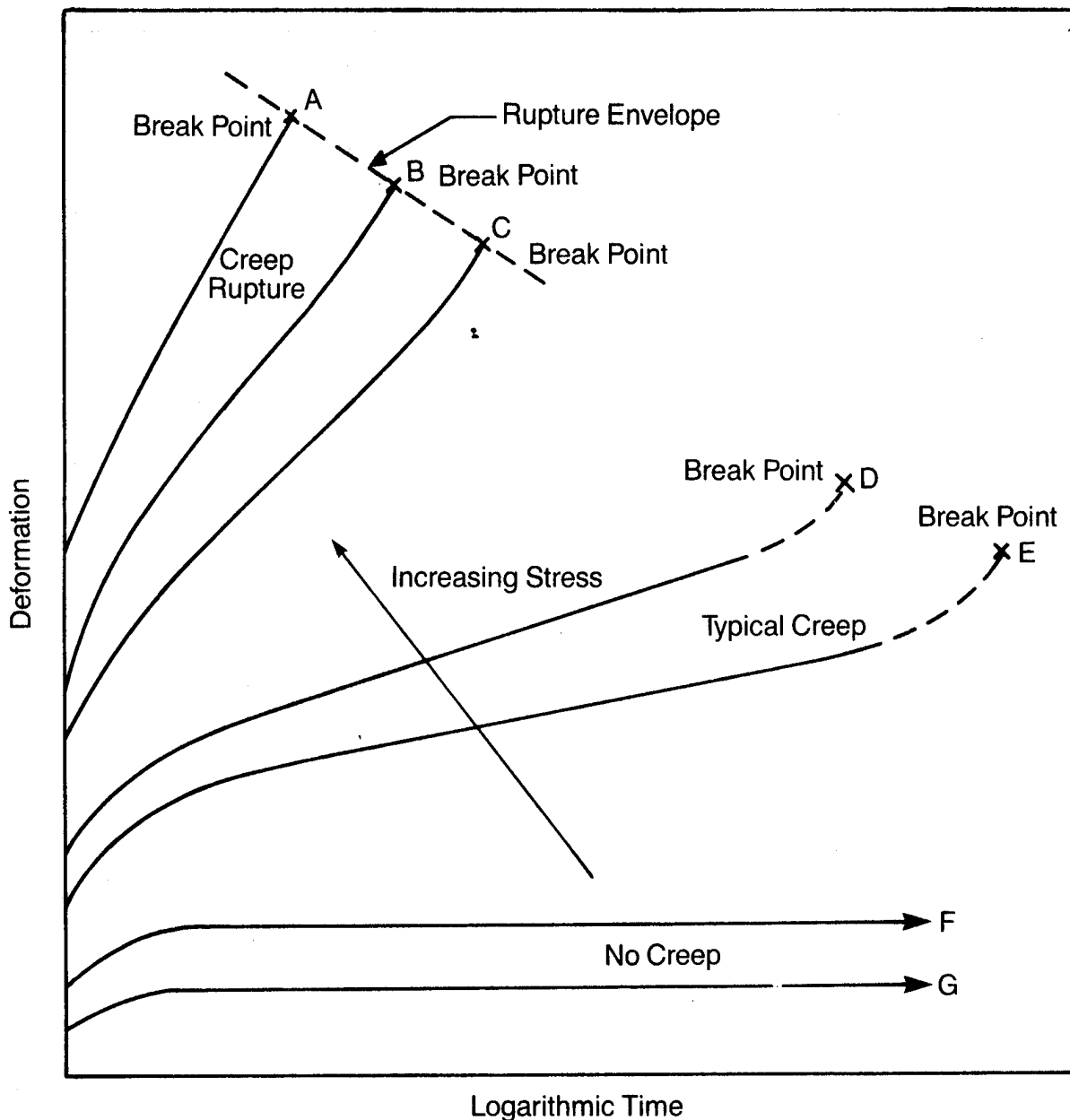


Figure 3-6. Deformation vs Time

The prediction of creep response for plastics relies heavily on experimental data coupled with reasonable extrapolation and other experience factors. It should be noted that Figs. 3-5 and 3-6 represent idealized creep curves and that in reality they differ somewhat due to the ductile or brittle nature of each material.

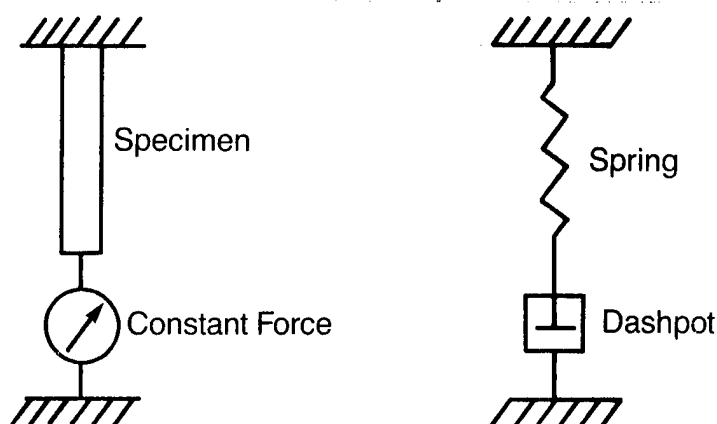
3-2.1.2 Stress Relaxation

The viscoelastic nature of plastic materials results not only in creep at constant stress but also in creep under constant strain. The creep is in the form of a relaxation of induced stress. Both the creep and stress relaxation responses are based on internal molecular movements, and a theoretical correlation exists between them.

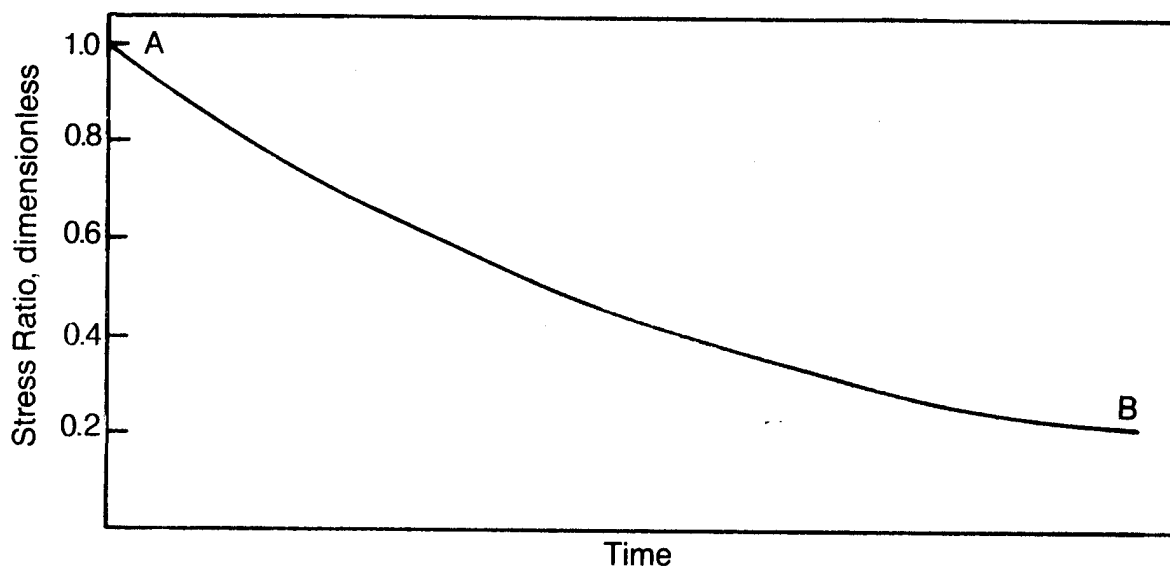
Although the stress relaxation phenomenon is im-

portant in certain design applications, it has not been as popular as creep in experimental analysis. Stress relaxation occurs when a specimen is instantaneously stretched or compressed to a fixed length that is held constant (Fig. 3-7(A)). This action results in an induced mechanical stress, which immediately begins to decrease, or relax, with time. The initial deformation is elastic and the internal relaxation or viscous flow occurs over time. Stress relaxation experimentation, as with that of creep, is performed primarily in tension. The other important mode of loading is compression, but little interest exists in this mode.

The typical stress relaxation response (Fig. 3-7(B)) is characterized by an initial induced tensile stress at essentially zero time. This stress (Fig. 3-7(B), point A) begins to relax with time and theoretically decays to zero



(A) Constant Strain Schematic



(B) Stress Relaxation

Figure 3-7. Tensile Stress Relaxation Model

stress (Fig. 3-7(B), points A to B). If the induced strain were removed at an interim time, there would be an immediate elastic recovery to a point dependent on the initial deformation.

3-2.2 LOW-RATE LOADING

The low rate of loading is characterized by what has been termed conventional stress-strain curves (Fig. 3-2). The practice, which has also been termed static testing and follows that developed for metals, is performed at constant rates of elongation with conventional testing machines.

Although categorized by strain rates (Fig. 3-3) between 10^{-5} and 1 s^{-1} , most testing is performed in the region of 10^{-2} and 10^{-1} s^{-1} . At these rates of loading, the initial response to the four-parameter model (Fig. 3-4) is essentially elastic and is followed by viscous flow as the load increases. For loads at which the elastic spring is completely stretched, all the remaining load is directed at viscous flow until rupture occurs.

Test data for the low rates of loading have been seriously challenged by some as having little use in design. Where applications encounter the rate of loading used in the test, there is relevancy in design use.

Low-rate loading is typified by stress-strain curves (Fig. 3-2). Ductile thermoplastics generally exhibit a small initial linear region, which yields to continuous viscous deformation as the stress is increased. For thermosets and nonductile reinforced thermoplastics, however, the response is more elastic, and there is little yielding. Characteristically, plastics do not exhibit a proportional limit, elastic limit, or yield point, and the elastic modulus determination is sometimes questionable. There are exceptions; some plastics do inherently exhibit the "metallike" response, particularly when reinforcements are incorporated.

3-2.3 HIGH-RATE LOADING

Although high-rate loading is considered to be as important as creep in military applications, the high-rate technology is not as well developed and data are very limited. This lack of data is principally due to the complexity of development of design theory, of experimentation, and of correlation of test data with theory.

When a plastic is subjected to a force at a high rate of loading, the response is quite different from the response experienced in the very low rate or creep environment. The chain-like molecules undergo a response predominantly manifested by molecular stretching or highly elastic behavior due to the short time of load application. Viscous behavior is almost nonexistent.

High-rate response is significantly affected by the strain rate (Refs. 4 and 5) and mode of loading. The strain rate values can be used to divide qualitatively the rate of loading into high, very high, or ultrahigh (Fig. 3-3),

depending on the mechanism used to induce the force. The division is quite arbitrary and highly machine dependent. Explosive or ballistic devices induce ultrahigh strain rates greater than 10^4 s^{-1} , whereas pneumatic, hydraulic, or mechanical devices can produce strain rates greater than 10^{-1} s^{-1} .

The method of loading implies the manner in which the force is applied, i.e., either induced when in intimate contact with the material or impacted onto the material, as typically encountered in a drop environment. Both methods involve transmittance of shock waves, the intensity of which is quite different. Another form of rate loading is the cyclic mode whereby a force is repeatedly applied.

A discussion of high-rate loading in terms of inertia, impact, and cyclic effects is appropriate and is given in the paragraphs that follow.

3-2.3.1 Inertia

Many high rate-of-loading applications are the result of a force that is in intimate contact with the material being applied rapidly to a body. Similar to the firing of a projectile or rotating machine mechanisms, internal components are subjected to the inertial effects due to acceleration. Loading can be in the form of tension, compression, shear, or torsion, and the result is a material having to withstand a mechanical load at the high strain rate.

The most common representation of this response is the stress-strain curve. The behavioral change generally results in higher ultimate strengths, an increase in the apparent stiffness or modulus of the material, and a corresponding decrease in ultimate elongation (Fig. 3-8). This change is much more pronounced for plastics than for metals.

Another major material characteristic of interest is the energy required to break or the energy-absorbing capabilities of the material; this characteristic is defined as the area under the stress-versus-strain curve. Units are expressed in joules (foot-pounds) of energy per unit volume of material. The energy to break at the various high rates of loading is excellent data for comparing materials and for elementary design analysis.

As illustrated in Fig. 3-3, the strain rate values are arbitrary and reflect only a relative ranking commensurate with available testing equipment. Testing at the high rate (between 10^{-1} and 10^1 s^{-1}) is prescribed in standard ASTM test procedures. For the very high and ultra high strain rates, there are no ASTM or other standard test methods. High-rate behavior has been investigated with the Split Hopkinson bar apparatus, but this device has not been formalized into a standard. It is the basis for data generation at strain rates between 10^2 and 10^4 s^{-1} , and the test is performed primarily in compression.

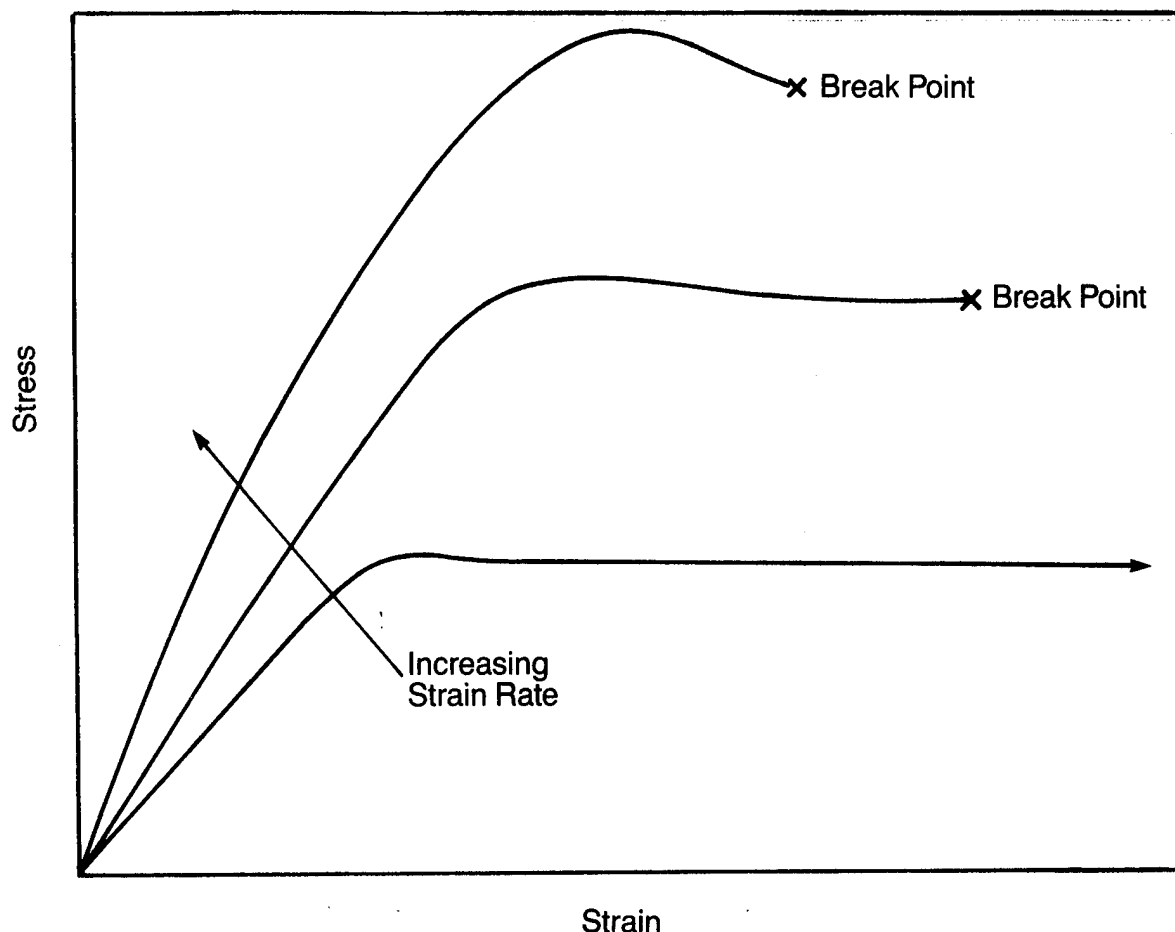


Figure 3-8. Tensile Stress vs Strain as a Function of Strain Rate

The lack of attention to high-rate loading is quite evident in the almost complete absence of material property data. Until greater interest is generated, this lack of data will remain a hindrance to effective design.

3-2.3.2 Impact

Impact is a high-rate loading in which a mechanical force, not initially in contact with the material, is impacted upon a body. Plastic response is again highly elastic and is influenced by the type of shock or impulse waves generated.

In the absence of both a sound theoretical approach and valid data, attempts are made to correlate the energy to break a material to that induced in the impact. The induced impact energy can be generally expressed in terms of available potential energy (drop height) or kinetic energy (velocity at impact) and can be categorized as being within the high or very high rates of strain (Fig. 3-3).

Impact data, as generally published in the trade, have not been completely useful in design because the standardized ASTM test methods have little resemblance to real-life impact conditions.

Although impact resistance is a key performance

requirement, the correlation of impact strain rates, material response, part geometry, temperature, and orientation of the part relative to the impact remains a most troublesome area. The development of high-rate impact test equipment may lead to a better understanding of material behavior and how to predict response.

3-2.3.3 Cyclic

Cyclic loading is a form of rate loading in which a stress is applied repeatedly to a material. Generally, the induced load is in direct contact with the material during the repeated motions. The frequency of the alternating load determines the rate of loading, which may be sufficiently rapid to induce inertial and vibratory effects. This form of loading is unique and is not generally characterized by the rates depicted in Fig. 3-3 but, rather, by an induced cyclic stress (Refs. 6 and 7).

At the start of cyclic loading, the chain-like molecules respond elastically but are soon influenced by internal frictional heating, whereupon the viscous response of the material may become evident. The temperature increase is very important in the resulting material behavior.

Greater interest is attached to the number of cycles required to produce failure, commonly referred to as

fatigue. As shown in Fig. 3-9, a plot of induced stress versus cycles to failure is the common method of describing response.

Fatigue testing is another area for which the test variables are numerous. Of the many modes of cyclic loading, i.e., tensile, compressive, flexure, and torsion, the only standard developed evaluates materials in flexure at a constant amplitude of force. The existence of only one standard indicates the limited attention paid to cyclic loading for plastics, although the variety of modes is recognized as pertinent to material characterization.

3-3 CREEP PROPERTIES

The most significant consequence of the inherent structure of plastics is the dependence of their flow behavior on time. The implications for the design life of the product are apparent because product failure can result as either stress rupture or excessive deformation (Refs. 10 and 11). The most basic property consideration in creep is deformational behavior. Also important are the properties of stress rupture and stress relaxation. Each of these properties is discussed in subsequent paragraphs.

For the most part, creep properties are based on simplified uniaxial tests that use standard specimen configurations because complex evaluation under combined static loading is costly. Combined testing is encouraged wherever possible to supplement the standard testing. Creep testing is performed principally in tension,

which is the area of greatest practical interest to designers, followed by compressive creep.

Creep testing assumes that the materials are relatively isotropic, i.e., that they have comparable properties in all directions. The assumption is reasonable in spite of the orientation effects that may exist for some materials. It should be remembered that anisotropic behavior, i.e., having unidirectional properties, is more complex and cannot be indiscriminately treated in a simplified manner.

Test data must be relied on to predict creep response until a suitable theoretical treatment is developed for nonlinear viscoelasticity. Until this treatment is available, experimental data will have to be adapted to the existing classical theory for elementary problem solving. The main difficulty designers face is the adaptation of uniaxial creep behavior to combined loading problems.

3-3.1 CREEP DEFORMATION

3-3.1.1 Tensile and Compressive Creep

Creep deformation testing, performed in accordance with ASTM D2990 (Ref. 12), provides basic data reflecting the time-dependent deformation in terms of creep strain. Generally, creep response is provided in tensile loading. Although the tensile mode of loading is most important in design, compressive creep is also important and must be evaluated accordingly. Compressive creep behavior varies somewhat from tensile behavior, particularly in rupture, but the data parameters and presentations are nearly identical.

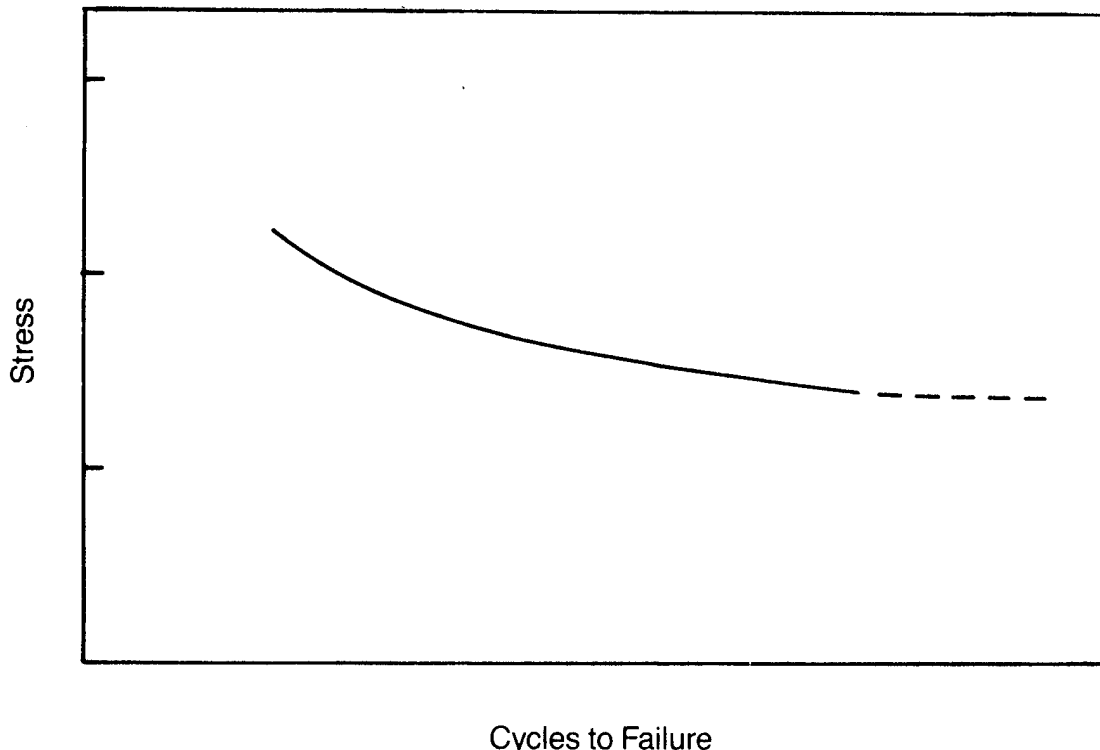


Figure 3-9. Tensile Stress vs Cycles to Failure

The test data should be provided nominally at ambient temperature and at several stress levels in order to depict the broad range of responses. When presented in graphical form, the data quickly reveal the variations of total strain versus time (Fig. 3-10) as a function of induced stress.

The significance of the deformation data is that the designer can obtain a representation of the strain that results from induced stresses in the time frame of interest. The analysis generally indicates material suitability in a creep environment.

Creep is significantly affected by environmental factors, principally temperature. Fig. 3-11 illustrates the variation in strain deformation as a function of temperature at constant stress. Materials affected by humidity or other environments also exhibit a modified response. Although it is impractical to conduct tests in all possible environments, materials known to be affected by a specific environment, e.g., moisture, should be evaluated in that environment.

Creep data are needed early in the design stage for specific design analysis or for general comparison with other materials. If complete creep data are lacking for a material assessment, designers should not consider using the material until either data are provided or creep performance is evaluated through material or prototype testing.

To facilitate the design process, creep data should include the basic material identification parameters (Table 1-2), the test conditions (Table 2-4), and those modified parameters described as follows:

1. *Type of Loading.* A verbal description of the method of loading. Creep testing should be performed in both tension and compression.

2. *Type of Specimen.* In tension, specimens should be Type I or Type II as specified in ASTM D638 (Ref. 13),

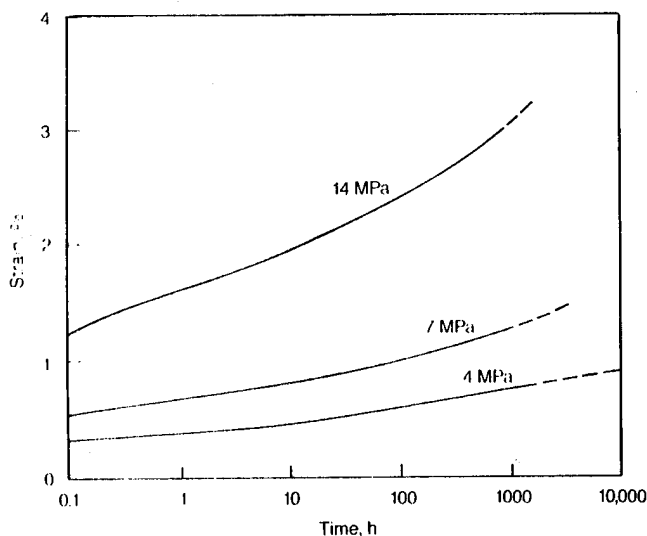


Figure 3-10. Tensile Strain vs Time as a Function of Stress

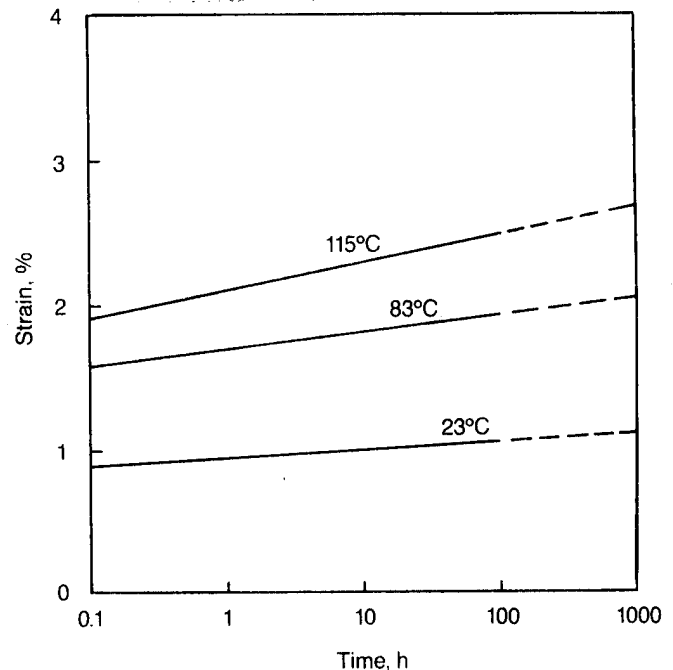


Figure 3-11. Tensile Strain vs Time as a Function of Temperature

and in compression, the unconfined specimen as specified in ASTM D695 (Ref. 14). Tensile specimens should have a nominal thickness of 3.18 mm (0.125 in.), and compression specimens should have a principal width or diameter of 12.7 mm (0.5 in.).

3. *Temperature.* A test condition at which each specimen should be evaluated. For creep the ambient and elevated temperatures should be 23°, 50°, 70°, and 90° C (73°, 122°, 158°, and 194° F), and as appropriate to the upper limit of the material.

4. *Stress Level.* The stress imposed on the specimen determined by dividing the load by the original cross-sectional area. At least three to five stress levels for each temperature shall be used, as suggested in ASTM D2990 (Ref. 12). These levels should include an upper stress level that is less than the one that produces failure in under 1000 h and a lower stress level that results in a nearly constant strain deformation for an extended time.

5. *Strain Deformation.* The creep deformation at each time interval, reported as the average total strain for the stress level. Reported in percent, it is the strain deformation multiplied by 100.

6. *Time.* The times at which the strain deformation is measured for the applied load. Conformance to the ASTM procedure is suggested i.e., 6, 12, and 30 min and 1, 2, 5, 20, 50, 100, 200, 500, 700, and 1000 h. Creep tests for a minimum of 1 yr are desired; time frames beyond 1 yr should be performed if practical.

7. *Standard Deviation.* The variability of creep strain at the time intervals at which measurements are made.

Creep data are conventionally plotted as total strain

deformation versus the logarithmic time, as shown in Fig. 3-11. The logarithmic plot is convenient because it usually results in a linear representation. Although presented graphically, the data should be supplemented in tabulated form for independent analysis or computerization.

Creep curves at various stress levels show a consistent trend, and it is often possible to interpolate between curves. Interpolation may be more difficult, however, if irregular patterns are exhibited, as may happen at high stresses and high temperatures.

If creep data are extrapolated to longer times, the extrapolation is normally indicated by dotted lines. Extrapolated data should be justified by the supplier to assure their validity. In all cases extrapolated data should not be extended beyond one decade of time.

Because long-term creep testing is time-consuming and expensive, attempts have been made to convert short-term creep data into long-term data. The principal methods used have been the Boltzmann superposition principle and the Williams, Landel, and Ferry (WLF) principle, among others. Most data generated by these methods are based on linear viscoelastic theory. These methods, normally applied by polymeric theoreticians and experimentalists, are limited in accuracy and should be used in design with extreme care. Thus creep data developed in this manner should be identified as such in the documentation.

3-3.1.2 Flexural Creep

Although flexural creep testing is performed, the data generated are less meaningful because

1. The induced stress is a combined tensile and compressive stress that varies across the specimen cross section.
2. The three- or four-point loading represents a special load configuration that cannot be generalized to other structures.
3. Many materials do not rupture.

Flexural creep testing should only be used as supplemental data for special applications; it should not be used to generate basic data for predicting creep response.

3-3.1.3 Creep Lateral Contraction

The creep lateral contraction, or Poisson's effect, is the ratio of lateral strain to longitudinal strain. It occurs in both tension and compression and is a fundamental parameter used to describe deformational behavior. The lateral contraction coefficient of specimens from the creep test is not generally provided in technical data due to the absence of a procedure in ASTM D2990 (Ref. 12). A creep lateral contraction procedure is described in Ref. 11.

The creep lateral contraction would help to solve design problems. In its absence, the Poisson's ratio, as determined in conventional tensile or compression strength tests, will suffice because this ratio should not appreciably affect results. Values of Poisson's ratio for plastics generally range between 0.3 and 0.5. Additional efforts are needed to establish test procedures to determine the lateral contraction effect.

3-3.1.4 Derivative Creep Data

From the basic creep deformation data (Fig. 3-11), other forms of data can be generated—isochronous stress versus strain, isometric stress versus time, and creep modulus (Fig. 3-12). Of the three, creep modulus is of greatest practical use in design.

Isochronous stress-strain curves (Fig. 3-12(D)) result from a cross-plot at constant time (Fig. 3-12(B)) of the creep strain for each stress level. At very short times (approximately 100 s) these curves approximate the conventional, constant rate of elongation stress-strain curves. The isochronous stress-strain curves are used in certain design problems to reflect the relative stiffness of materials when a specific time of loading is pertinent to the application.

Isometric stress versus time (Fig. 3-12(A)) results from a cross-plot of the data at a constant strain (Fig. 3-12(B)) deformation. This plot is rarely reported because it has limited use in design.

The most important cross-plot derived from creep data is creep modulus versus time (Fig. 3-12(C)), which is the result of dividing an initial, applied constant stress (Fig. 3-12(B)) by its strain and then plotting the value for the corresponding point in time. Such a plot provides the designer with the means to predict deformation, as described in a subsequent paragraph.

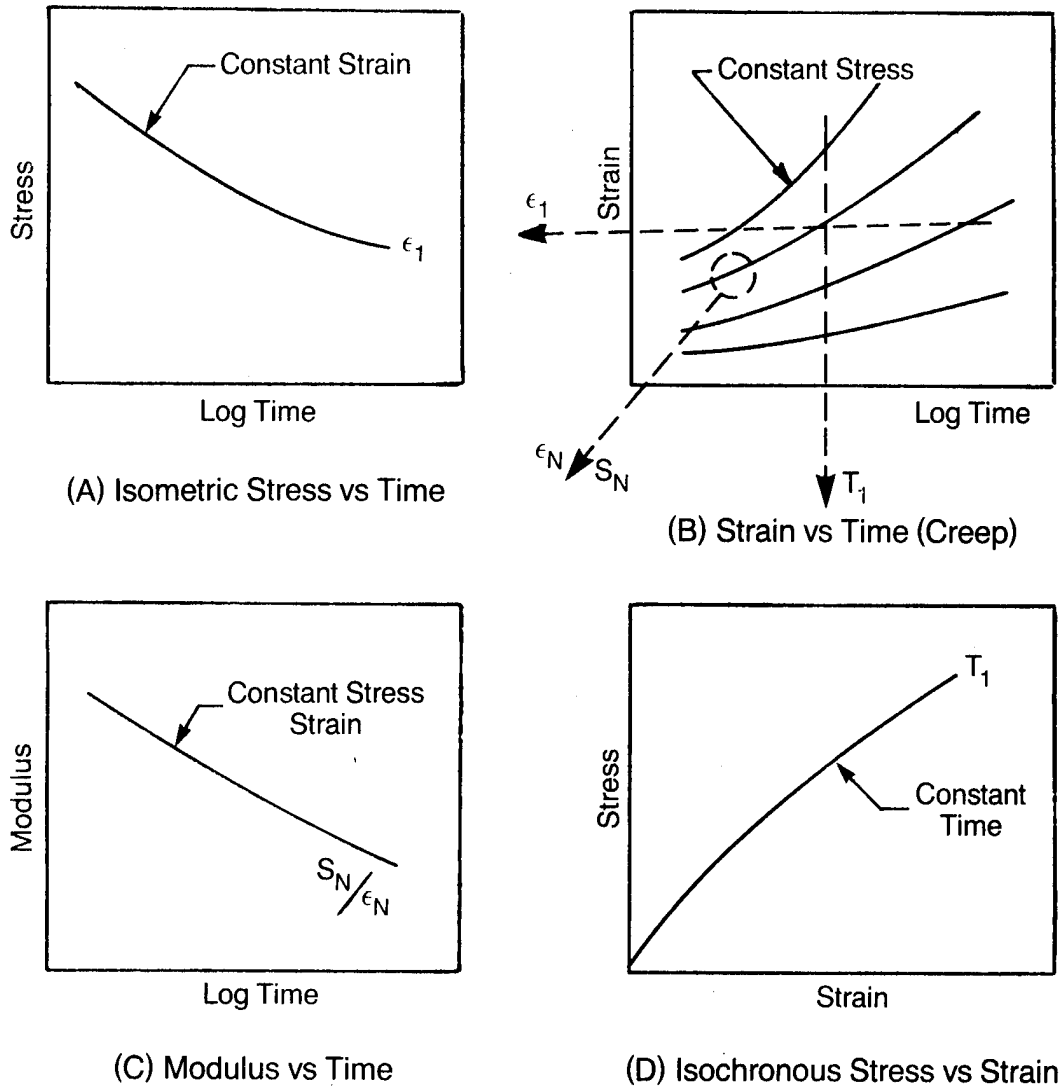


Figure 3-12. Creep and Creep Modulus

3-3.2 CREEP RECOVERY

The concept of creep recovery was introduced as a typical response in plastics. When a material experiences deformation as a result of a constant load, a portion of that deformation is recovered if the load is removed, and the induced elastic strain reached at the time the load was removed decreases. Further decrease occurs with time (a creep curve in reverse) until most of the deformation is recovered. This behavior has practical application when plastic components are subjected to intermittent, long-term stresses.

However, because there is no procedure to reflect the need, creep recovery data have not been generated to any extent. Testing could be an extension of basic creep tests, i.e., ASTM D2990 (Ref. 12), with deformation being measured with time following the removal of the load. There is a definite need to promote the requirements for data generation through ASTM procedures.

3-3.3 CREEP MODULUS

Creep modulus, sometimes referred to as "apparent modulus", is defined as the ratio of the initial, applied stress to the creep strain. It is a calculated value of the basic measurements made for creep strain or deformation and is the parameter used in the simplified analysis for predicting plastic deformation (Ref. 1). Creep deformation is time dependent; therefore, creep modulus is also time dependent.

Theoreticians have defined an associated term, "creep compliance". It is the reciprocal of creep modulus, i.e., the ratio of the time-dependent strain to stress, and it has limited use in the simplified design procedures discussed in this handbook.

Creep modulus computed from creep deformation data is normally plotted, as illustrated in Fig. 3-13, against log time. The slope of the line reflects the relative loss of stiffness as a plastic undergoes creep. Creep modulus

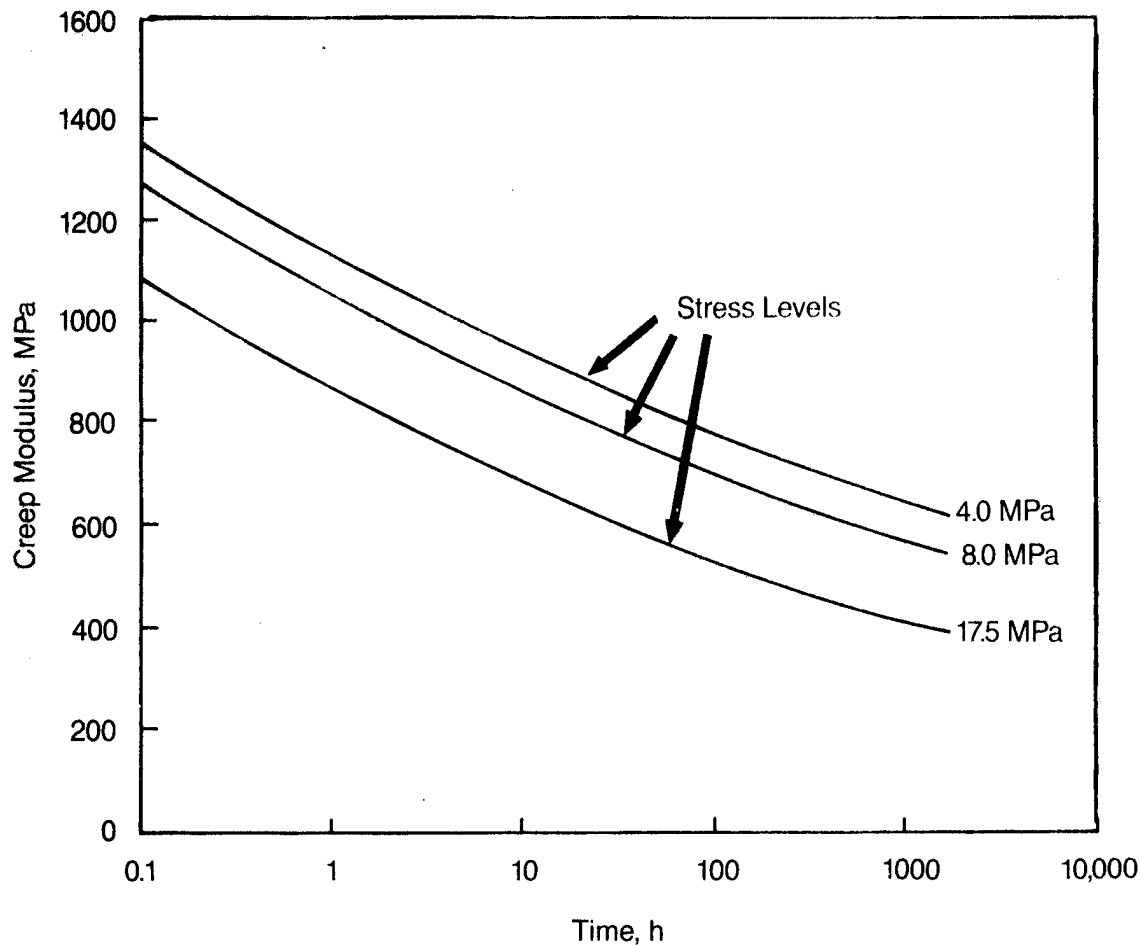


Figure 3-13. Tensile Creep Modulus vs Time

versus time is also plotted on log-log scales and provides convenient linear presentations.

Because creep modulus is a calculable function of creep deformation, the test parameters that are derived for the basic creep data apply. This fact also implies that the interpolation and extrapolation of creep data also apply.

The applicability of creep modulus to design is comparable to that for metals as used in the classic design equations, except that the time-dependent modulus must be used. Thus the interaction of stress and strain is dependent on a variable modulus. This dependency implies that a stress imposed on a product will induce a strain of variable magnitude that is dependent on the time frame being considered.

3-3.4 CREEP RUPTURE

The phenomenon of creep rupture (Fig. 3-6) occurs at relatively high stresses, i.e., those approaching the ultimate strength of the material as measured by conventional, short-term tensile tests (ASTM D638 (Ref. 13)). As the level of stress is reduced, the time to rupture increases. A point is reached at which the stress will not produce rupture even if the stress is applied for a very long time.

Creep rupture is a necessary adjunct to normal creep behavior. It is important in design because it indicates the short life that can be expected when relatively high loads or stresses are applied to a material on a continual basis. Thus creep rupture is used to establish the limit at which working stresses may be induced.

Prior to extended creep tests, common practice in ASTM D2990 (Ref. 12) is to evaluate creep rupture by determining the stress versus time to failure to establish the point at which creep strain versus time is to be evaluated. Testing is performed at several stress levels to produce rupture within 3000 h. From the point data a creep rupture envelope is defined that reflects the load-bearing capability at the test temperature as shown in Fig. 3-14. Elevated temperature and environmental factors, especially in tension, have a significant influence on performance. In fact, many product failures identified as stress cracking can be attributed to stress rupture resulting from exposure to a hostile environment.

The decrease in the value of the rupture stress with time has also been referred to as static fatigue (Ref. 11) because the curve shape (Fig. 3-14) is analogous to the phenomenon of dynamic fatigue under cyclic loading, in which stress at

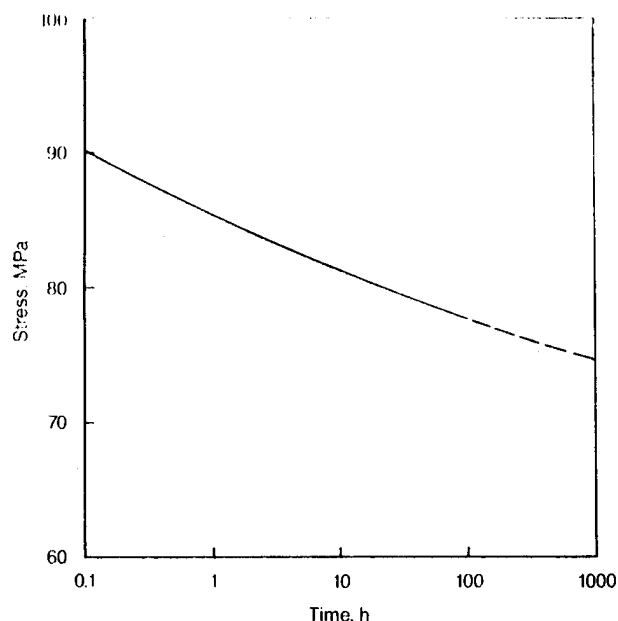


Figure 3-14. Tensile Creep Rupture Envelope

failure decreases with the number of cycles. However, the terminology "static fatigue" is incongruous and should be disregarded.

The "creep rupture envelope" is normally plotted on either log-log or semilog coordinates. This usually results in a nearly linear relationship of stress versus time to failure, which can easily be used to abstract data for use in design analysis. Generally the creep rupture envelope reflects catastrophic failure for relatively brittle materials or the onset of failure characterized by excessive yielding, flowing, or drawing for ductile materials.

Testing for creep rupture is primarily performed in tension because ductile plastics do not, in essence, rupture in compression or in flexure. Flexure creep testing is undesirable, as discussed previously, but creep rupture-type testing should be performed in compression because response to compressive loading is important in applications development.

Creep rupture data should include the basic material identification parameters given in Table 1-2, the test conditions given in Table 2-4, and those parameters in ASTM D2990 (Ref. 12) unique to the test described as follows:

1. *Type of Specimen.* In tension, specimens should be Type I or Type II as specified in ASTM D638 (Ref. 13), and in compression the unconfined specimen should be as specified in ASTM D695 (Ref. 14). Tensile specimens should have a nominal thickness of 3.18 mm (0.125 in.) and compression specimens should have a principal width or diameter of 12.7 mm (0.5 in.).

2. *Temperature.* A test condition at which each specimen should be evaluated. For creep the ambient and elevated temperatures should be 23°, 50°, 70°, and 90°C

(73°, 122°, 158°, and 194°F), and as appropriate to the upper limit of the material.

3. *Stress Level.* The stress levels—determined by dividing the applied load by the initial cross-sectional area—selected to produce rupture for the specified time periods

4. *Time.* The time at which rupture occurs for each of the applied stress levels. Conformance to ASTM procedure is suggested—i.e., 1, 10, 30, 100, 300, 1000, and 3000 h.

Creep rupture data—like normal creep data—may be extrapolated but should not exceed one decade of logarithmic time. Again, such data should be justified by the supplier to assure that the extrapolation has not been carried out indiscriminantly.

3-3.5 STRESS RELAXATION

Stress relaxation tests, performed in accordance with ASTM D2991 (Ref. 15), provide data used to predict the reduction of stress in materials subjected to constant deformation. Tensile or compressive loading is encountered in applications in which materials are joined with mechanical fasteners or screw thread closures, which must remain tight throughout the life of the product.

Stress relaxation is defined as the stress decay, which is equal to the difference between the applied stress and the stress remaining at the given elapsed time. Of significance in design are the stress that remains at long times and the ability of the product to perform its function.

Typical stress relaxation data normally will reflect the decay at a number of stress levels and at ambient temperature (Fig. 3-15). The data are most useful when plotted in the form of stress relaxation versus time on log-log coordinates. The result is nearly straight-line diagrams, which facilitate interpolation and extrapolation.

Stress relaxation data developed in tension and compression should include the basic material identification parameters (Table 1-2), the test conditions (Table 2-4), and those parameters (ASTM 2991 (Ref. 15)) unique to the stress relaxation described as follows:

1. *Type of Loading.* A verbal description of the method of loading. Creep testing should be performed in both tension and compression.

2. *Type of Specimen.* In tension, specimens should be Type I or Type II, as specified in ASTM D638 (Ref. 13), and in compression the unconfined specimen should be as specified in ASTM D695 (Ref. 14). Tensile specimens should have a nominal thickness of 3.18 mm (0.125 in.), and compression specimens should have a principal width or diameter of 12.7 mm (0.5 in.).

3. *Temperature.* A test condition at which each specimen should be evaluated. For creep the ambient and elevated temperatures should be 23°, 50°, 70°, and 90°C (73°, 122°, 158°, and 194°F), and as appropriate to the

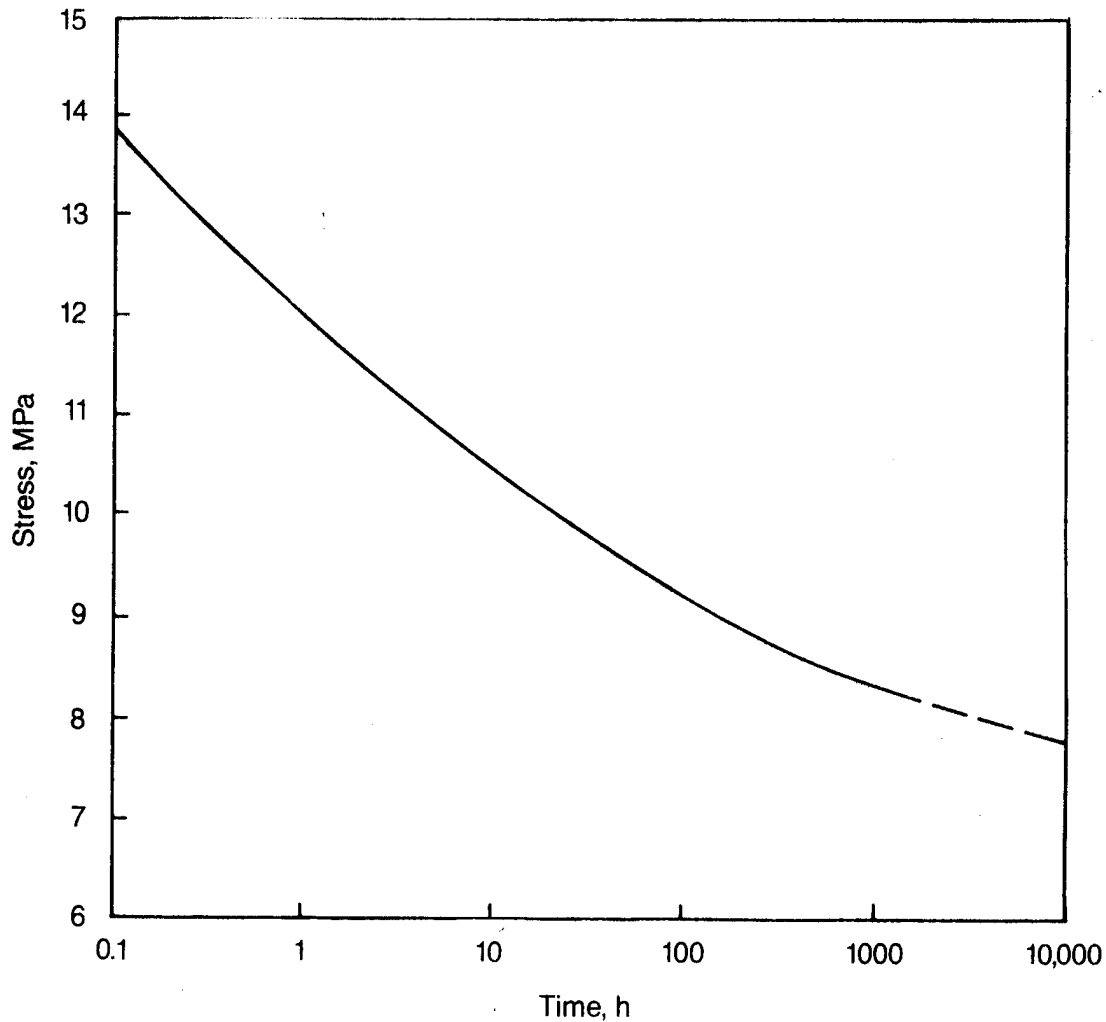


Figure 3-15. Tensile Stress Relaxation

upper limit of the material.

4. *Stress Level.* The stress imposed on the specimen determined by the ratio of load measurement to the original cross-sectional area and recorded at the initial strain and at the elapsed time periods.

5. *Time.* The times at which stress is measured during the constant strain extension. Conformance to the procedure in ASTM D2991 (Ref. 15) is suggested, i.e., immediate and as prescribed up to 1000 h.

6. *Strain Deformation.* The initial extension of the specimen in terms of total initial strain in percent.

The theory of linear viscoelasticity can conveniently link the stress relaxation response to creep deformation so that data for each are used to calculate the other. However, data generated are limited to the linear viscoelastic region, and this limitation should be stated in reported results. Stress relaxation data are useful in predicting the reduction of stress in materials, particularly in materials used in plastic fasteners or seals.

3-4 STRESS-STRAIN PROPERTIES

The stress-strain properties of plastics discussed in this paragraph are intended to clarify their use in engineering. This review, however, does not contain all the requirements necessary to satisfy end use needs because engineering for plastics in dynamic environments requires further development.

Although the relationship of the applied stress-to-strain deformation is an important form of mechanical property data for plastics, it has limited use in engineering design due to the practice in the trade to report data only for limited test speeds—usually those between 5.1 mm/min (0.2 in./min) and 508 mm/min (20 in./min). Because plastics are sensitive to rate of loading, they must be tested over a broad range of conditions. Furthermore, common practice is to report only point data—ultimate strength, modulus, and elongation—which cannot be used to describe adequately material behavior to mechanical loading (Ref. 12).

Also the design process is hindered by other factors:

1. The problem of defining the rate of loading and load distribution in a product
 2. The lack of experimental data to substantiate theoretical predictions
 3. The limitation of existing data because they are developed from simple coupon specimens rather than from combined loading.
- Thus the designer must still rely, for the most part, on approximations.

Another factor leading to the absence of rate-of-loading data is the general lack of user demand for data, which possibly results from the designer's difficulty in defining needs for dynamic end use conditions. This difficulty, coupled with the complexity and cost of testing over a full range of rates, results in a lack of incentive for material suppliers to develop fully stress-strain property data.

What is required for plastics is greater emphasis on technology development at rates of loading greater than 10^{-1} s^{-1} (Fig. 3-3) complemented by basic user education in how to adapt high rate data to applications. Stress-strain data are required to complete the rigidity and strength requirements as a counterpart to the creep environment. The testing technology for high rate testing is continually being developed (Refs. 16 and 17). Although existing ASTM procedures do provide for a range of loading rates, additional standard test methods are necessary for the very high rates of loading.

With regard to creep properties, materials are assumed to be relatively isotropic. Experience has shown, however, that plastic materials do exhibit anisotropic behavior due to orientation effects. Such effects must be considered in the generation of all mechanical stress-strain data.

The paragraphs that follow describe the procedures available to generate stress-strain data. In this chapter emphasis is placed on tension, compression, and shear properties. Although flexure properties are widely reported in the trade literature, they have not been included in this handbook because they are considered to have value only in engineering design applications involving flexure. This limitation is implied in ASTM Test Method D790 (Ref. 18), which does mention the usefulness of flexural properties in design but only for quality control and specification purposes. ASTM Test Method D790 (Ref. 18) also indicates other limitations of the test procedure. To encourage the costly generation of flexural data when greater efforts should be directed to produce badly needed tensile and compression data appears incongruous. Furthermore, it is questionable whether the data derived are valid due to anisotropy, stress distribution, and the mode of loading. Again, generated flexure data are useful only for the type of beam test from which measurement was made. For design using the tensile and

compressive properties to calculate the flexural behavior of a plastic seems more desirable.

The most useful forms of stress-strain data are the ones for tension and compression loading. Although the tests are based on simplified uniaxial loading, they provide the most fundamental properties adaptable to the classical theory of elasticity. Related interest exists for the shear properties and Poisson's effect.

3-4.1 TENSILE STRESS-STRAIN

Useful stress-strain data for plastics can be generated using the procedures outlined in ASTMs D638 and D2289 (Refs. 13 and 19). These two test methods do not include all rates of loading but do provide the basis for many of the desired dynamic conditions. ASTM D2289 (Ref. 19) provides useful data for plastics engineering design, encompassing the load-time range described in the standard. ASTM D638 (Ref. 13) is the conventional method and is useful as the datum for all rigidity and strength data.

Initially, tensile stress-strain data should be provided at ambient temperature for a range of loading rates. When provided in graphical form, the results will pictorially reflect the relative sensitivity of the material to the rate of loading (Fig. 3-16).

Properties are principally affected by temperature; therefore, each test rate should be applied to a broad range of temperatures (Fig. 3-17), from well below freezing to well above the boiling point of water. This broad range is essential in engineering design.

Stress-strain data should include the basic material identification parameters (Table 1-2), the test conditions (Table 2-4), and those parameters unique to the stress-strain test as described as follows:

1. *Type of Loading.* A verbal description of the method of loading, e.g., tensile

2. *Type of Specimen.* The primary types of specimens in tension should be Type I or IV, as specified in ASTM D638 (Ref. 13). If other types are preferred because of the nature of the material, they should be in addition to Type I or IV. The nominal thickness of tensile specimens should be 3.18 mm (0.125 in.).

3. *Temperature.* A test condition at which each specimen should be evaluated. High-rate testing at low and elevated temperatures should include -55° , -25° , 0° , 23° , 50° , 70° , and 90°C (-67° , -13° , 32° , 73° , 122° , 158° , and 194°F), and as appropriate to the upper limitation of the material.

4. *Rate of Straining.* The initial rate of straining ($\text{m/m}\cdot\text{s}$ ($\text{in./in.}\cdot\text{s}$)) of the specimen, which is equivalent to the associated ASTM speeds of testing—i.e., 5 mm/min, 500 mm/min, 2.5 m/min, 25 m/min, and 250 m/min (0.20 in./min, 19.69 in./min, 8.20 ft/min, 82.02 ft/min and 820.21 ft/min)—specified in the test method

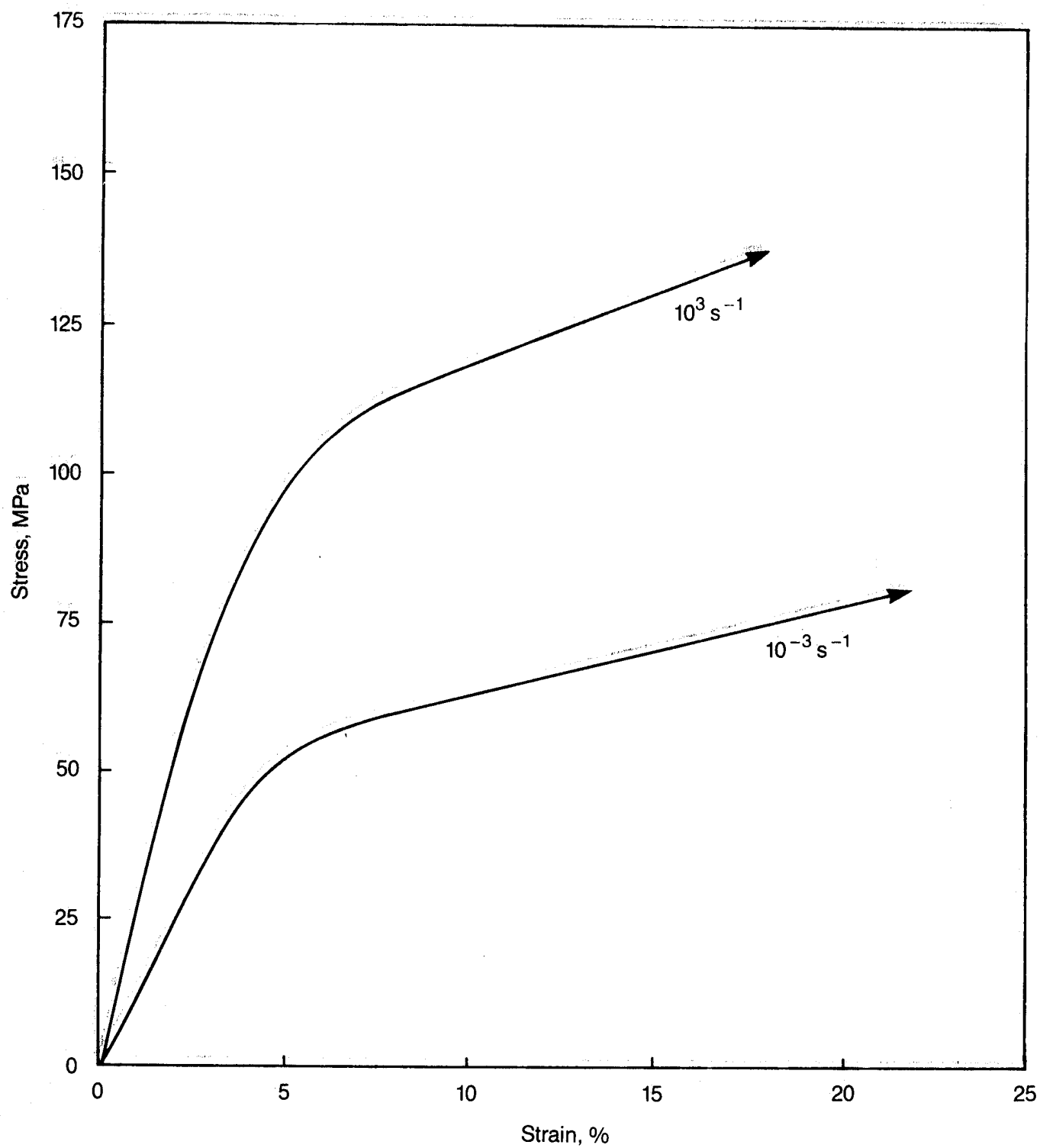


Figure 3-16. Stress vs Strain as a Function of Strain Rate

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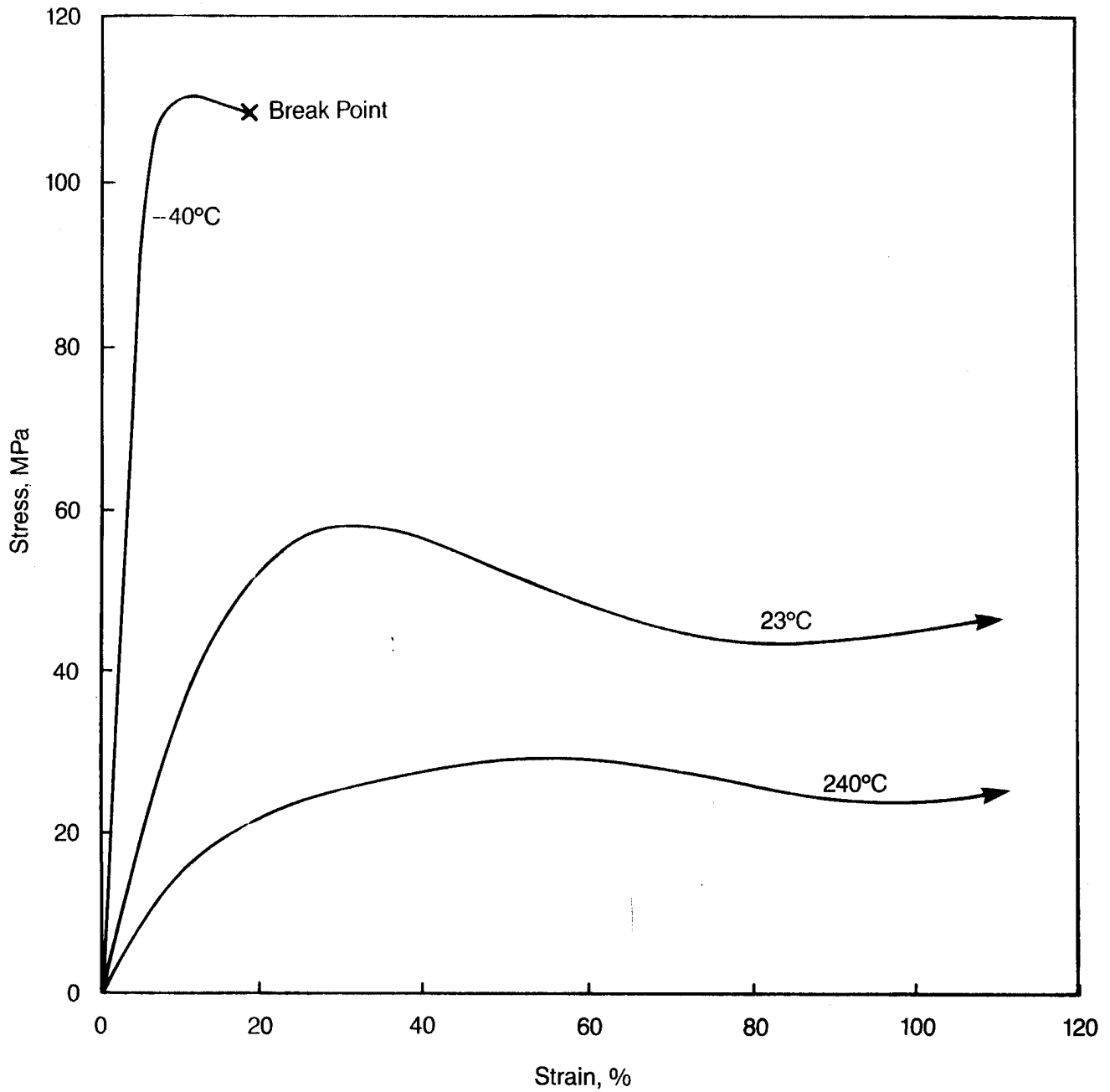


Figure 3-17. Stress vs Strain as a Function of Temperature

5. *Stress*. The nominal stress induced in the specimen at each level of strain and determined by dividing the load by the original cross-sectional area

6. *Strain*. The ratio of the deformation to the original length of the specimen

7. *Standard Deviation*. The variability of the stress at the strain intervals at which measurements are made.

The stress determined, based on the original cross-sectional area, is termed "engineering stress". This is a more practical determination compared to "true stress", which is based on the cross-sectional area at the point of measurement.

The stress-strain data for plastics, when represented by a curve, provide an assortment of characteristics useful to the designer (Fig. 3-18). They are as follows:

1. *Ultimate Strength*. The maximum stress sustained by the material prior to rupture. This stress typically occurs near the point of rupture.

2. *Ultimate Elongation*. The maximum strain encountered or the strain at the point of rupture. The value of strain at rupture is a measure of the ability of the specimen to undergo large deformation before fracture.

3. *Yield Point Range*. Conventionally defined as the point at which excessive deformation will occur without further increase in stress. Not easily determined for most plastics, the yield point expressed as a value of stress is in most cases ambiguous and requires graphical representation to be completely understood.

4. *Tangent Modulus*. Conventionally known as the elastic, or Young's, modulus and defined as the slope of the initial portion of the stress-versus-strain curve below the proportional limit. Tangent modulus is a measure of the stiffness of the material or its resistance to deformation. Because the linearity of the initial portion of the stress-strain curve is limited, determination is difficult; hence the value for the modulus of elasticity is ambiguous.

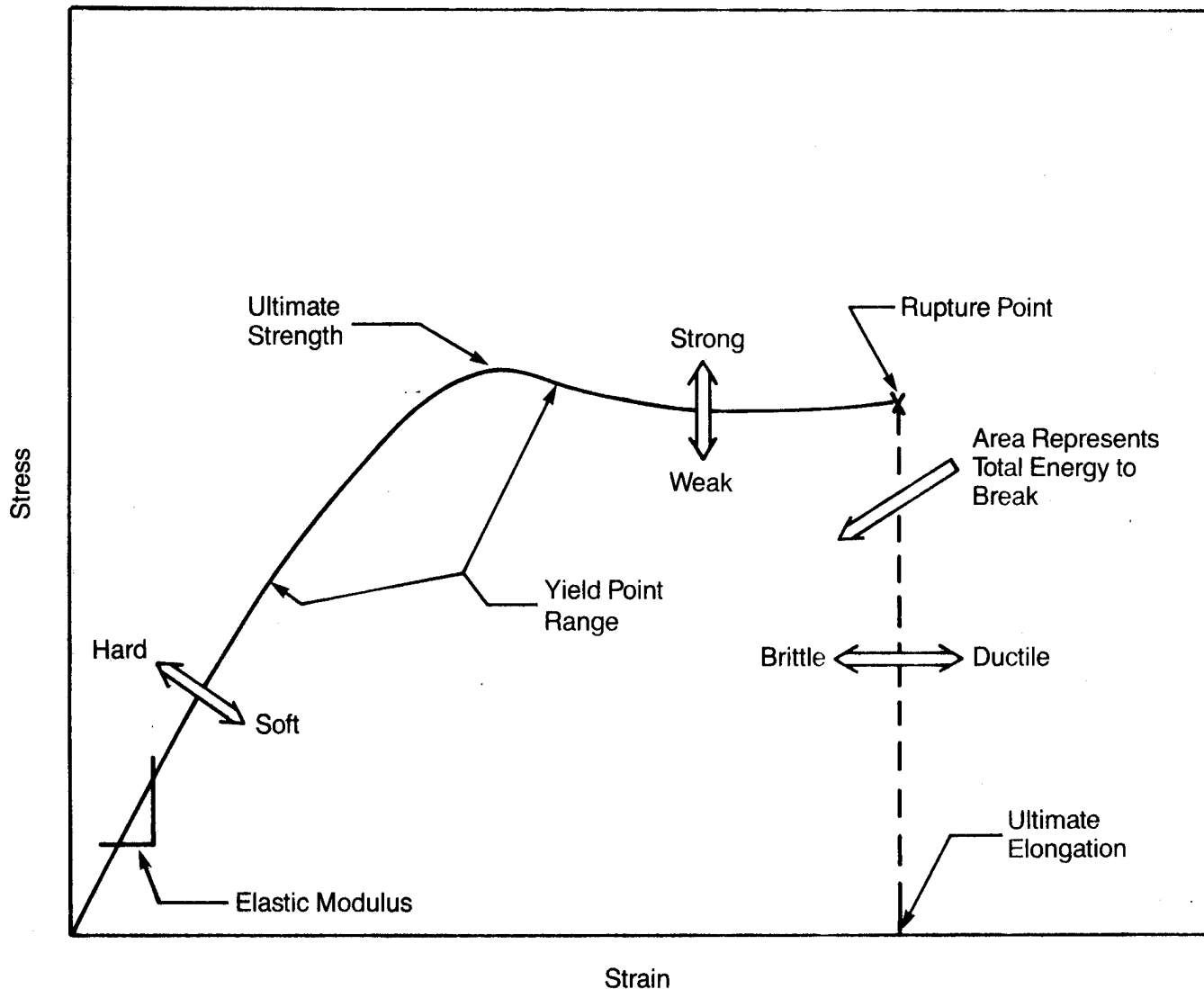


Figure 3-18. Stress vs Strain

A graphical representation is required to apply the concept of modulus properly.

5. *Area Under Stress-Strain Curve.* A measure of the energy-absorbing capabilities of the material (Fig. 3-18) in terms of the energy required to break a unit volume of material. Ductile or tough materials are characterized by large areas, which indicate high ultimate elongation. Brittle materials, although they may exhibit high strength and modulus, have small areas due to low ultimate elongation.

As outlined in the Annex to ASTM D638 (Ref. 13), other terms associated with stress-strain curves are proportional limit, elastic limit, and associated yield strength. These terms have not been described in this handbook because their determination for most plastics is difficult and for the most part nonexistent. Also attempts to specify values for these terms could be misleading.

It should be apparent from the foregoing that the assessment of stress-strain properties should be left to the user. Comprehensive test data provided in prescribed formats are of greatest benefit to designers.

Conventionally stress-strain curves are provided in graphic form by material suppliers and experimentalists. An even more convenient method is to represent the engineering data as equations. A third method is to provide the data in tabular form. In general, it may not be possible to read graphs accurately, equations may be difficult to adapt to plastic data, and tabular stress-strain data do not visually depict material response. However, for most effective use, tensile data should be provided in tabular form and supplemented by graphical representation. Also tabular and/or graphical representations require both average values and the standard deviation of stress for the intervals of strain. The rupture point should be defined by the nominal stress and strain and by the standard deviation. Also tabular data are valuable because they are more readily adaptable to computerized form, which is becoming very useful in analytical assessments.

Engineering design problems caused by high rates of loading involve two principal elements. The first, as discussed in the foregoing paragraphs, is to know how the rate of load application influences properties; the second is to know how to analyze the dynamics problem. This process can be addressed in either a highly theoretical or an extremely simple manner. In the analysis for creep the simple approach is preferred because of the complexity of the theoretical analysis and the difficulty in obtaining accurate experimental data.

The tensile properties as suggested herein will provide sufficient data for use with the classical equations developed for the analysis of elastic materials. The primary material characteristic is the time-dependent modulus, which must be derived from data at the comparable rate of load application for the product. When this derivation is done, more accurate response prediction should be possible.

Another common method used to analyze material behavior at high rates of loading is the strain-energy concept. Strain energy is the work done by the external forces producing the stress and is represented by the area under the stress-strain curve, as previously described. This strain-energy concept can be applied in the elastic range in which all the induced energy is recoverable. Plastics at high rates of loading exhibit more elastic behavior; therefore, the strain-energy concept should be applicable. Experimentation is required to validate this premise.

Although the strain-energy concept is usually applied to elastic deformation characteristics, it may be applied up to the rupture point of a material. The total area under the stress-strain curve represents the energy required to deform and rupture a unit volume of material. This theory is extremely important in the comparison of material resistance to high-rate loading and is potentially useful for designing for impact. The strain-energy concept, however, oversimplifies the problem. Other factors such as shape, load distribution, and mode of loading also influence performance.

3-4.2 COMPRESSIVE STRESS-STRAIN

Although compressive response to loading has not gained the same attention as its tensile counterpart, it remains a most important part of applications development. Compressive stress-strain data are currently developed using ASTM D695 (Ref. 14), which is the only generalized, standardized test procedure for plastics. Because it recommends testing at only one speed, its use is extremely limited and it inherently inhibits the generation of compression data.

Compressive properties of plastics require an assessment comparable to that of tensile properties, i.e., initial testing at ambient temperature at a range of loading rates followed by testing at a broad range of temperatures.

Testing plastics in compression is essential because in most cases their rigidity and strength behavior differ from those in tension. Specifically, the modulus of elasticity and the mode of failure are significantly different.

The test data for compression should be developed in a manner comparable to that used for tension (par. 3-4.1). The same strain rates and temperatures should be used. Testing should use a specimen configuration of the type described in ASTM D695 (Ref. 14), i.e., a right cylinder 12.7 mm × 12.7 mm × 25.4 mm (0.5 in. × 0.5 in. × 1.0 in.), with a slenderness ratio in the range from 11 to 15:1.

The derived results should be stress-versus-strain data in tabulated form supplemented with a graphical representation. Both representations require the average values of stress and strain and their respective standard deviations.

The engineering properties derived from the data are comparable in terms of indicating rigidity, yielding,

strength, and strain energy. All of these data are useful in simplified analysis and in material comparisons. However, the most serious hindrance to deriving the foregoing information is the lack of a standardized test method for the various rates of loading. None exists other than the one for the single, conventional speed listed in ASTM D695 (Ref. 14). Perhaps application of higher speeds of testing could be employed, but the complexity of the instrumentation must be addressed. Therefore, a definite need exists to develop test procedures for high-rate compression testing. The experimentation being directed at high-rate data has focused on the split Hopkinson pressure bar apparatus (Refs. 17, 20, 21, and 22). This apparatus has been used to a limited extent to evaluate high-rate effects.

The split Hopkinson device is used at strain rates approximating 10^3 s^{-1} . Materials are evaluated in compression with a small, cylindrical specimen. Other equipment has been used (Refs. 14, 20 and 22) to evaluate the medium strain rate—between 0.5 s^{-1} to 50 s^{-1} —effects in compression with similar type specimens.

High-rate material property data in compression are virtually nonexistent. Until a standardized procedure is developed, a serious void will continue to exist for those dynamic applications of importance to the military.

3-4.3 POISSON'S RATIO

The Poisson's effect for plastics, described in par. 3-2.1 as the creep lateral contraction coefficient, has been measured to a limited degree in standard tensile testing. Poisson's ratio is currently measured according to the method in ASTM E132 (Ref. 23), which was developed for structural materials and is used readily in the equations developed for the classical theory of elasticity.

Conventionally, the test method determines the change in transverse, cross-sectional area when the material is subjected to a longitudinal tensile deformation. It has been developed for use with isotropic, elastic materials at stress levels below the proportional limit and for low rates of loading. Experimental research (Ref. 24) revealed that this ratio for plastics is dependent on material structure, temperature, rate of strain, strain level, and time. Although Poisson's effect for metals under normal use has been considered to be relatively constant, these given variables should significantly influence Poisson's effect for plastics from the creep environment to loading at high rates.

Thus data generation for Poisson's effect is hindered by the lack of an effective test procedure for measurement. The only available procedure (ASTM E132 (Ref. 23)), developed for metals, is unsuitable because it is mainly related to metallic material response to tensile loading.

For most materials Poisson's ratio in tension varies between 0.20 and 0.50. The value of 0.5 is a particular case in which the volume of the material remains constant. In reality, the volume of a material increases when it is

subjected to a tensile stress, and this increased volume results in values less than 0.50. For plastics Poisson's ratio in tension varies from 0.30 to 0.50. It has to be assumed that these values were derived at very low rates of loading and at ambient test conditions. Values for Poisson's ratio under other conditions of test are generally not available.

Because the response of plastics becomes more elastic at high rates of loading, Poisson's ratio may be used to advantage in the basic elastic relationships, which relate the shear and bulk moduli to the elastic modulus. These relationships are defined as follows:

$$G = \frac{E}{2(1 + \mu)}, \text{ Pa (psi)} \quad (3-1)$$

$$B = \frac{E}{3(1 - 2\mu)}, \text{ Pa (psi)} \quad (3-2)$$

where

G = shear modulus of elasticity, Pa (psi)

E = elastic modulus of elasticity in tension, Pa (psi)

B = bulk compressive modulus, Pa (psi)

μ = Poisson's ratio, dimensionless.

Available values of Poisson's ratio have been used with these equations.

The lateral contraction of viscoelastic materials is a complex phenomenon that is complicated by the many variables including high-rate testing. Poisson's ratio must be evaluated to determine the influence of strain rate and temperature. Testing technology and data generation should conform to what is outlined for the tensile stress-strain curves.

3-4.4 SHEAR PROPERTIES

Although shear properties of plastics are important in engineering design, shear data are almost nonexistent. Shear is a main consideration in the classical theory of elasticity, yet the developments in experimentation and data production have been primarily directed at tension. If shear data are reported, they generally consist of a single point, punch shear value. Shear properties of interest include strength, modulus, and toughness characteristics typically deduced from shear stress-strain curves.

There are two types of shear as shown in Fig. 3-19: direct shear and pure shear. Direct shear (Fig. 3-19(A)) is produced by applications employing fasteners or by the confined punch-type mode loading, whereas pure shear (Fig. 3-19(B)) is induced shear stress, which is the result of torsion, combined tensile and compressive loading, the bending of beams, or the direct application of a force in the parallel plane mode. The response of viscoelastic materials to shear in these modes of loading is funda-

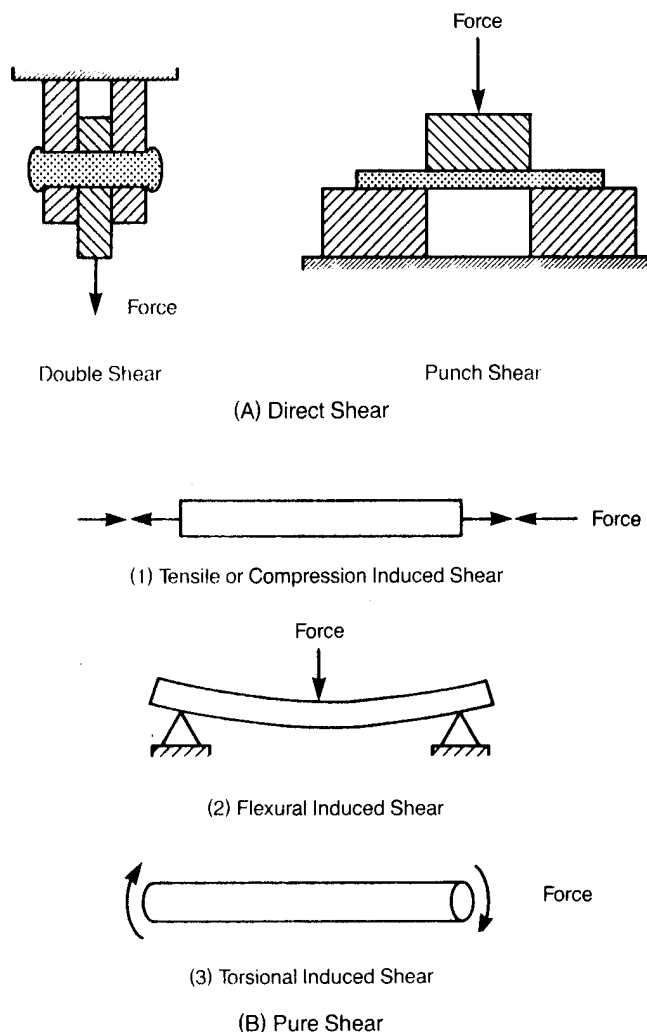


Figure 3-19. Types of Shear

mental to their use. The two types of shear require independent assessment, as established in appropriate ASTM test methods.

Direct shear testing is a unique end use condition of loading. This mode of loading normally restricts the material motion and results in confined deformation prior to rupture. The analysis required in this application is a simple calculation related to shear strength, i.e., force divided by area. ASTM D732 (Ref. 25) provides a method intended solely for this type of application. The simplicity of this method warrants generation of data to suit this specific mode of loading. ASTM D732 (Ref. 25) is limited in the variables that should be investigated. In addition to high-rate effects, two of the more significant parameters are thickness and temperature. Shear data as a function of these two variables would be sufficient for most static-type conditions of loading. Investigation of direct shear strength as a function of rate of loading is valuable for component evaluations encountered in missile or projectile firing environments. These three variables would result in a substantial amount of useful engineering data.

The average value of shear strength in megapascals, or pounds per square inch, developed from ASTM D732 (Ref. 25) should include the basic material identification (Table 1-2), the test parameters (Table 2-4), and those test variables unique to the shear test and described as follows:

1. *Dimensions of Specimen.* Due to the influence of thickness on the shear strength, the thickness range should include 1.6 mm (0.0625 in.), 3.18 mm (0.125 in.), 6.35 mm (0.25 in.), and 12.7 mm (0.5 in.).

2. *Temperature.* Tests should be conducted at ambient temperature (23°C (73°F)), at elevated temperatures of 50°, 70°, and 90°C (122°, 158°, and 194°F), and as appropriate to the upper limitation of the material.

3. *Speed of Testing.* The speed of testing should include 1.27 mm/min (0.05 in./min) as a datum and 5.1 mm/min (0.2 in./min), 508 mm/min (20 in./min), 2.54 m/min (100 in./min), 25.4 m/min (1000 in./min), and 254 m/min (10,000 in./min).

The information derived from these variables is represented in Fig. 3-20. Shear strength generally increases with thickness but will naturally decrease with temperature. As influenced by strain rate, shear strength should increase with an increase in rate of loading and decrease with temperature.

The only other significant test method for pure shear is ASTM D1043 (Ref. 26). This method is used to calculate the shear modulus of rigidity, which is termed "apparent" because the specimen may be deflected beyond the elastic limit. Thus the results do not represent the true modulus of rigidity and have limited value in engineering use.

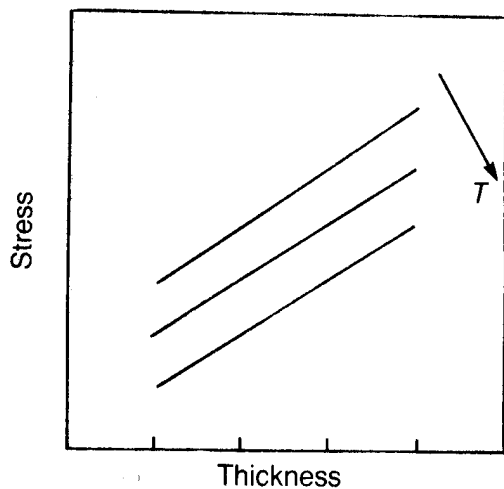
Until a shear stress-versus-strain test procedure is adequately defined and standardized, Poisson's effect should be used to determine the modulus of rigidity. Although Poisson's ratio also has limited usefulness as described in par. 3-4.3, it is a more practical interim technique for use in design problems.

3-5 IMPACT RESISTANCE

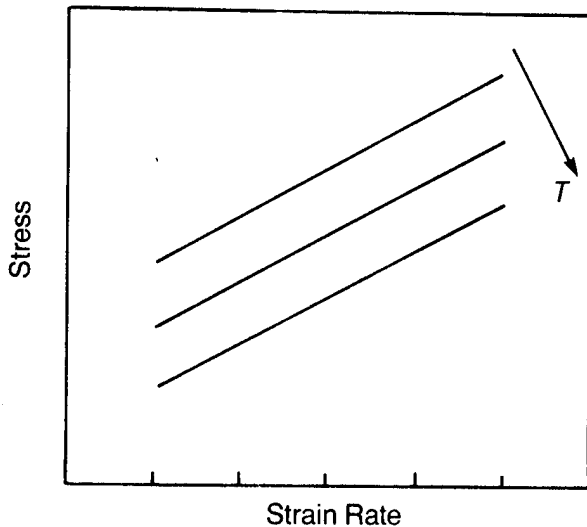
The resistance of a material to impact, or its toughness, is a key performance quality in most applications because impacts or dropping of a product is a common occurrence. Impact is a form of high-rate loading in which one body encounters, or impacts, a second body at a relative velocity. This action results in a unique form of wave propagation through each body, the response of which is quite complicated.

Despite many years of materials research and development, the quantitative prediction of material response to impact is still one of the most troublesome areas in design. This fact is due to the lack of an analytical procedure capable of predicting impact resistance and the lack of test methods to evaluate material performance.

The discussion in this paragraph centers on drop impact. Impact of the type encountered in a ballistic



(A) Shear Stress vs Thickness

 T = temperature

(B) Strain Rate as a Function of Temperature

Figure 3-20. Shear Stress vs Thickness and Strain Rate as a Function of Temperature

environment, e.g., in a projectile fired from an explosive or pneumatic device, is not considered because it is a highly-specialized application.

Currently, designing for impact is complex and depends heavily on confirmatory testing of the product itself. The difficulties in predicting response are caused by the number of factors that influence impact performance. These factors include the rate of impact loading, the geometry of the specimen, the influence of small radii and flaws (notches), the concentration of the load, effects of repeated impact, and the many environmental factors (particularly temperature). Although there is a multitude

of variables, laboratory testing is essential to assess relative material resistance to impact.

The most widely reported form of impact data developed is for the Izod-type test addressed in ASTM D256 (Ref. 27). It is a pendulum-type test that measures the energy required to break a specimen. Although the test is popular, the Izod test data have little value in engineering design (Refs. 28 and 29) because reported values can lead to erroneous conclusions regarding the relative impact resistance of materials. The associated types of pendulum tests, the Charpy method (ASTM D256 (Ref. 27)) and tensile-impact (ASTM D1822 (Ref. 30)), also have limited ability to predict drop impact resistance. Therefore, use of these methods in material assessments should be discouraged. They should be used only for their intended purposes, i.e., quality control and material specifications.

Two of the standard test methods considered amenable to practical measurement of impact resistance for materials are ASTM D2289 (Ref. 19) and ASTM D3029 (Ref. 31). ASTM D2289 (Ref. 19) was described in par. 3-4.1 as being useful in assessing the total energy to failure of a material. Although the test is conducted at controlled and selected strain rates, it is limited because the high-rate tests are uniaxial and therefore quite different from the multiaxial impact stresses that occur in actual use. Also it is a tensile test and thus does not consider compressive impact applications.

These limitations may lead to poor correlation with actual product or drop impact performance. However, the test produces results that should be a fair assessment of relative, inherent material toughness, and should negate the influence of velocity at impact. Suitable performance, however, would still require prototype testing.

Of all the established test methods, the drop weight test described in ASTM D3029 (Ref. 31) appears to provide the most realistic way to assess relative material toughness. The test employs a falling ball, or "tup", which is dropped onto a flat plastic sheet. The weight and/or height of the ball are varied to determine the level of potential energy that will produce failure in 50% of the specimens. Failure is defined as the presence of any crack or split. Deformation should be noted accordingly wherever it occurs.

The drop weight test also is best at duplicating conditions encountered in real drop environments. The impact produces a type of multidirectional and somewhat concentrated impact stress. Actual products can be subjected to the drop weight test for comparison with testing of plastic sheet. The test has limited strain rate capability, but in spite of this and the qualitative means of establishing a failure criterion, the drop weight test is the preferred method of measuring impact resistance and should be used until more suitable high-rate test methods are developed.

The drop impact test data (ASTM D3029 (Ref. 31)) should include the basic material identification (Table 1-2), the test parameters (Table 2-4), and those variables unique to the impact test and described as follows:

1. *Type of Specimen.* The plastic sheets should be 3.18 mm (0.125 in.) thick to promote further standardization in testing.

2. *Temperature.* Drop impact testing should be conducted at ambient temperature (23°C (73°F)) and low temperatures of -55°, -25°, and 0°C (-67°, -13°, and 32°F).

3. *Test Conditions.* The preferred test for relative material assessment is Procedure B, which uses a constant drop height of 0.660 m (26.0 in.) and a clamped specimen. This procedure is preferred, as stated in ASTM D3029 (Ref. 31) because more uniform and meaningful data are produced.

4. *Mean Failure Energy.* A measure of the relative resistance to breakage of a plastic sheet in terms of the energy required to produce 50% failures

5. *Failure Mode.* A description of the type of failure that includes terms such as crack, split, indentation, shatter, or other observed condition.

It is apparent from the foregoing discussion that engineering design for impact needs further development. A method is needed by which to evaluate and adapt all the variables effectively according to an appropriate equation for predicting response. Until such a method is available, the drop weight impact test should be adequate to compare materials and correlate material and product performance.

Although the current technology used to evaluate impact properties as defined by the availability of ASTM procedures is limited, promising developments have been made in high-rate impact testers (Refs. 29, 32, and 33). The testers, which are of proprietary design, vary in configuration; however, they are capable of providing variable input modes of loading and of recording material response. The adaptability of these testers to practical measurement of material toughness would give significant impetus to effective design.

3-6 FATIGUE PROPERTIES

Material failures under repeated cyclic stress at below their static breaking strength are well recognized. Fatigue is a failure mechanism long associated with metals and described in terms of fatigue life or fatigue properties. Properties are reported in terms of fatigue strength, which is the value of cyclic stress of a specific character that a given specimen sustains before failure.

The response of plastics to a cyclically applied load is generally more complex than it is for metals. This increased complexity is the result of nonlinear viscoelastic behavior of plastics, their low conductivity, and their sensitivity to temperature. The various modes of fatigue

loading produce significantly different results for plastics (Ref. 1).

The effect of molecular structure on fatigue life has been investigated to a limited degree. The effect is not generally viewed in terms of the four-parameter model (Fig. 3-4) because fatigue behavior involves molecular flow changes in the degrees of crystallinity and crystal morphology, and it involves the breaking of polymer chains. A major factor in this response is the internal heat buildup and thermal softening.

Testing for fatigue strength may be performed in three modes: uniaxial (tension and/or compression), flexure, or torsion. Although the uniaxial and torsional loading are relatively straightforward, flexure testing can be formed by cantilever beam, simple beam, or by a rotating beam method. In each the induced stress (Fig. 3-21) can vary significantly from a mean of zero to many nonzero conditions. These testing modes and the many test variables combine to magnify the potential test data.

The testing of plastics for fatigue strength is conducted in accordance with ASTM D671 (Ref. 34), which is used to provide data to guide in the selection of materials. Direct use in design is limited, principally because the testing is flexure and the test conditions are unique.

Testing in accordance with ASTM D671 (Ref. 34) should include the basic material identification parameters (Table 1-2), the test conditions (Table 2-4), and those modified parameters described as follows:

1. *Type of Loading.* A verbal description of the method of loading, i.e., "flexure"

2. *Specimen Temperature.* The temperature of the specimen during the test, which includes the temperature at failure

3. *Frequency.* For a relative comparison of materials, the frequency should be 30 Hz.

4. *Mean Stress.* For a relative comparison of materials, the mean stress should be zero.

5. *Fatigue Strength.* The value of induced stress at failure is N cycles.

6. *Failure Mode.* A description of the type of specimen failure in terms of fracture, softening, overheating, or reduced stiffness by cracking

7. *Cycles.* The number of cycles N at which specimen failure occurred.

The result of fatigue testing is the generation of an $S-N$ curve (Fig. 3-22), i.e., a plot of stress versus cycles to failure (log scale). The curve is obtained by testing many specimens to failure for different stress levels. For metals the curve illustrates that the cycles to failure increase as the stress is decreased. A point is reached at which the further reduction of induced stress does not cause the material to fail. This point is called the fatigue limit or endurance limit. Stresses less than the fatigue limit do not cause failure, regardless of the cycles tested. For many polymers the fatigue limit is between 20 and 35% of static

tensile strength; others may not show a definite limit. Also there is a question as to whether such a limit exists for plastics because there is a general lack of data to substantiate the fact.

The *S-N* curve produced from ASTM D671 (Ref. 34) has very limited use in design; it represents only one mode

of loading. However, it forms the basis from which material comparisons can be made. Other test conditions may produce results that reverse relative rankings. This speculation necessitates that fatigue testing be expanded beyond the limitation of the single ASTM procedure.

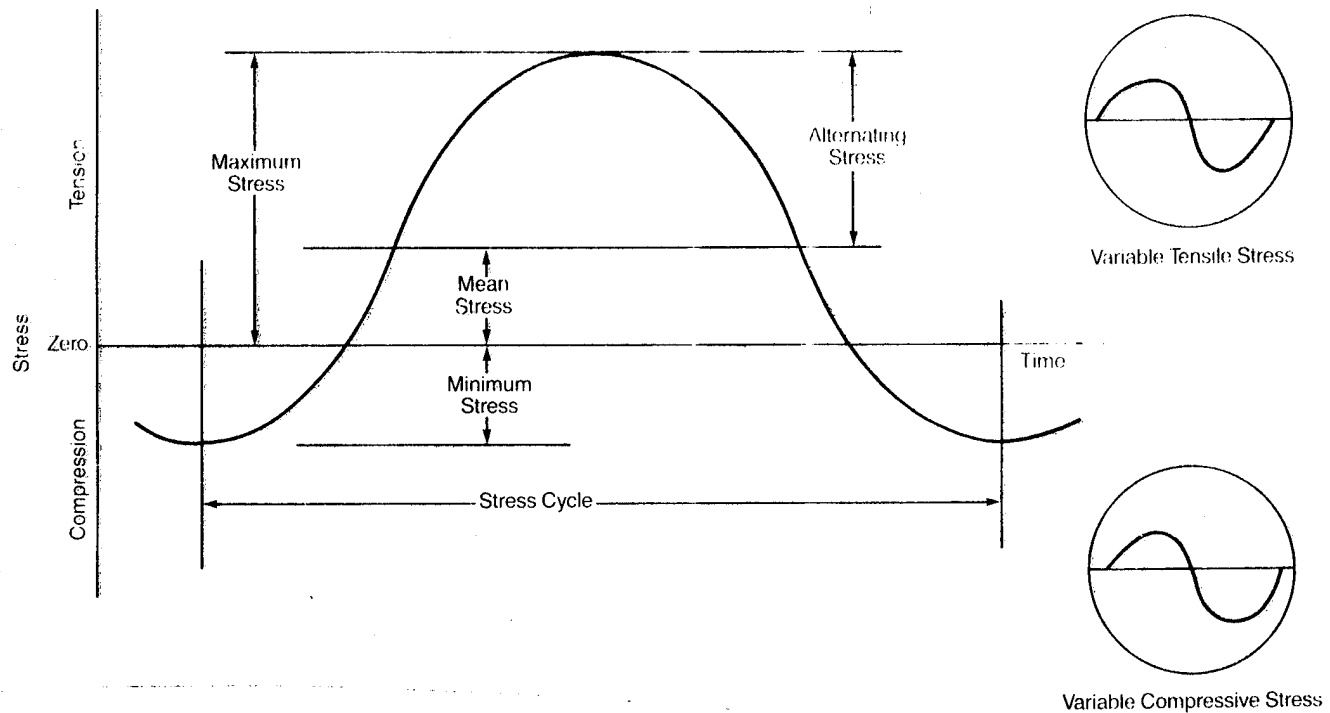


Figure 3-21. Cyclic Loading

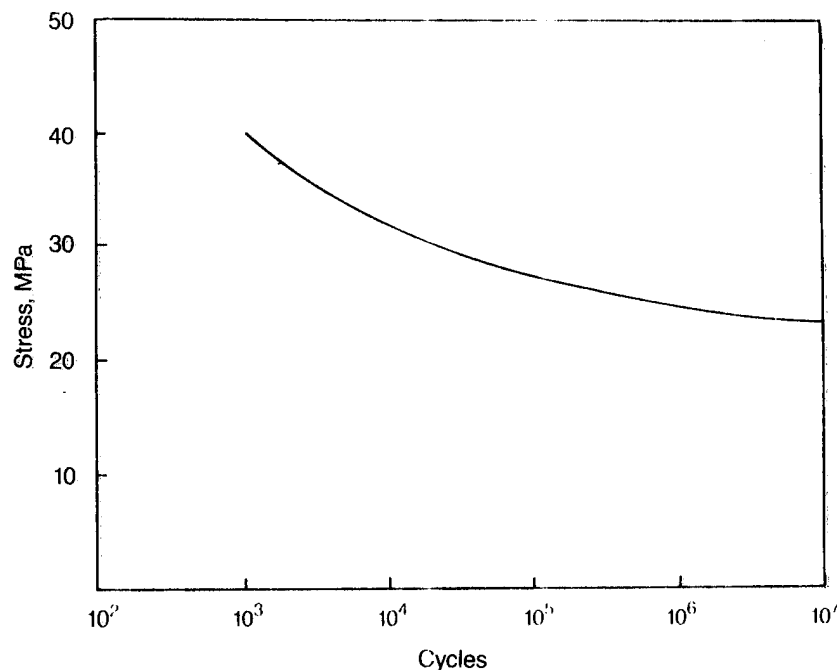


Figure 3-22. Fatigue Failure Envelope

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CHAPTER 4

THERMAL PROPERTIES

Thermal properties for plastics encompass two major groups. One group is associated with thermophysical changes, and the second group is associated with decomposition in terms of burning characteristics. The thermophysical properties include thermal expansion, conductivity, and transition temperatures. The data parameters and their engineering significance are discussed for each thermal property.

4-0 LIST OF SYMBOLS

T_g = glass transition point, °C (°F)

T_m = melting point, °C (°F)

β = secondary transition temperature, °C (°F)

γ = secondary transition temperature, °C (°F)

4-1 INTRODUCTION

Thermal properties for plastics incorporate a wide range of material characteristics that center on the behavior caused by exposure to thermal environments. Properties discussed in this chapter focus on the changes in the physical or chemical structure of a plastic and do not include the temperature effects on other properties discussed elsewhere in this handbook, e.g., mechanical or electrical properties discussed in Chapters 3 and 5, respectively. The thermal properties in this handbook are divided into two groups. The first is thermophysical, and the second relates to thermal decomposition.

When heat is applied to a plastic, the plastic absorbs the heat, transfers it throughout the mass of material, and concurrently undergoes physical change. These thermal responses, called thermophysical properties, are used to predict and/or better understand plastic behavior. When a large quantity of heat is applied to a material, decomposition occurs; when subjected to a flame, the material undergoes another form of thermal decomposition. This behavior, broadly termed flammability, represents a unique response that has severe consequences in end use applications.

The thermophysical properties are those inherent or physical characteristics that change due to temperature exposure. For instance, when heat is gradually applied to a material, the volume of the material increases due to increased molecular activity. When additional heat is applied, many plastics undergo transitional changes, the end result of which may be the transition from a solid to a liquid, i.e., melting. These responses are reversible and are solely the result of increased thermal activity; hence they are called thermophysical properties.

The second group of thermal properties relates to high-heat environments, in which irreversible changes result. The decomposition may affect product performance or,

in the case of fire, may have serious consequences for people and property. Although some materials do not burn, their decomposition products, smoke and gases, are more hazardous than flame itself.

The measurement of thermal properties has been conducted for many years by test methods referred to in this chapter as "traditional". There was a need, however, to evaluate quickly material characteristics for both research and production use. This need for quick evaluation resulted in test equipment developments categorized under the term "thermal analysis", i.e., the measurement of properties as a function of temperature. Four specific techniques have evolved:

1. Differential scanning calorimetry (DSC)
2. Thermogravimetric analysis (TGA)
3. Thermomechanical analysis (TMA)
4. Differential thermal analysis (DTA).

These methods typically measure weight gains and losses, dimensional changes, and heat flow and are preferred over the traditional test methods.

Testing for thermal properties, as for most properties, may require elaborate equipment or test procedures. This fact is not obvious in the discussion that follows because it is assumed that those performing the tests attend to all test details. Therefore, the requirements, as stated in this chapter, represent an oversimplification of the test methods involved. The emphasis of the discussion is on the engineering significance and the output form for design use.

4-2 THERMOPHYSICAL PROPERTIES

Of the thermal properties categorized as thermophysical, a few interest designers. They are thermal expansion coefficient, thermal conductivity, specific heat, diffusivity, the crystalline melting point, and glass transition temperature. Principally these properties describe the absorption of thermal energy and the changes that occur in the physical state of a material. For plastics, these properties are significant because plastics are poor conductors of heat, expand readily, and have relatively low melting points.

Attempts are made to include within this category of thermal properties those that reflect the heat stability of a

plastic. Properties such as heat aging and continuous use temperature are typical, but they are more properly classified as permanence properties because they consider long-term behavior and, more importantly, are associated with the retention of other properties. Accordingly, heat aging and continuous use temperature are discussed in Chapter 8, "Permanence Properties".

The properties discussed in the paragraphs that follow are not strict material constants because they depend to some degree on temperature (Refs. 1 and 2). Also the properties relate only to the solid state of plastics. The thermodynamic characteristics in the liquid or melt state are of little interest in design and therefore are not considered.

The crystalline melting point and the glass transition temperature, discussed later in this chapter, are two unique transition temperatures described for plastics. Basically, the transition temperature is the point at which the material undergoes a physical change. The melting point is a major transition point and represents the well-known change from the solid to the liquid state. However, not so well known is the glass transition temperature, which is one of many transitions that occur in the solid state and is of utmost importance in design. It represents the point at which a polymer will undergo a molecular change from a hard, brittle state to a softer, rubbery state.

4-2.1 THERMAL EXPANSION COEFFICIENT

When materials are heated, they generally expand, and when cooled, they contract. This change occurs in all directions and can be seen in the volume expansion of a specimen. For plastics, this thermal expansion and contraction characteristic is very important because the rate of change for plastics is approximately ten times greater than it is for metallic materials. In designing with nonmetals, both dimensional interface and induced stress (Ref. 3) must be considered across the entire end use temperature range.

A degree of control of the thermal expansion coefficient for plastics is achieved with the use of inorganic fillers. Added to the basic plastic, the fillers reduce the thermal coefficient in proportion to the amount used and, for certain plastic compositions, to the point at which the coefficient is comparable to that of metals. This reduction is achieved by the filler reducing the molecular mobility of the polymer (Ref. 4). Although the coefficient can be altered to suit the particular application, fillers may alter other desired characteristics of the base material, particularly mechanical properties.

Testing for the coefficient of linear thermal expansion has been traditionally conducted and reported in accordance with American Society of Testing and Materials (ASTM) Test Method D696 (Ref. 5). ASTM Test Method D3386 (Ref. 6) is another test procedure available to

measure the linear coefficient. An ASTM method used to measure the volumetric coefficient, ASTM Test Method D864 (Ref. 7), was available but has been discontinued. Of the two available test methods, ASTM D3386 (Ref. 6) provides a more thorough and simplified means of meeting design needs.

ASTM D3386 (Ref. 6) provides for the determination of the linear coefficient by use of the thermomechanical analyzer. This device enables determination of a wider temperature range than is available in ASTM D696 (Ref. 5). Also it is capable of recognizing other thermal observations, such as phase changes or transition temperatures, that tend to obscure expansion coefficient determinations. Due to these capabilities and to its simplicity, the thermochemical analyzer described in ASTM D3386 (Ref. 6) is suggested for testing of the linear coefficient of thermal expansion.

ASTM D864, which has been discontinued, was developed to determine the reversible cubical thermal expansion of plastics. The test used the dilatometer apparatus, as does ASTM D696, but provided for testing over a broader temperature range. For engineering use, however, in the determination of the volume expansion, it can be assumed that for homogeneous materials the cubical coefficient is linear in each of the principal directions (Ref. 8). This assumption is practical for engineering applications.

The coefficient of linear thermal expansion represents the unit change in dimension per degree of temperature change and assumes that the physical change is due to inherent molecular motion. Testing is directed at minimizing the effects of moisture, loss of plasticizer, molded-in strain, and anisotropic orientation (Ref. 9). In design these factors are evaluated independently and are usually superimposed on the thermal expansion determination.

Testing for the linear coefficient of thermal expansion should be performed in accordance with ASTM D3386 (Ref. 6). Testing should include

1. Specimen identification, as shown in Table 1-2
2. Common test parameters, as shown in Table 2-4
3. Those parameters unique to the test.

Parameters unique to the test are

1. *Thermal Linear Expansion Coefficient.* The average value of the coefficient of linear thermal expansion per degree Celsius

2. *Temperature.* Testing shall be performed over a temperature range from -20° to 80° C (-4° to 176° F) and at lower or higher temperatures, depending on the material.

The thermal linear expansion coefficient is used in the determination of dimensional change that would occur when a material is subjected to a temperature change. The coefficient has been expressed as centimeter per centimeter per degree Celsius but is conventionally expressed simply as per degree Celsius because it is derived on a per unit basis.

Most values of the thermal expansion coefficient reported in the literature for plastics at 20°C (68°F) vary from $6 \times 10^{-5}/^{\circ}\text{C}$ to $10 \times 10^{-5}/^{\circ}\text{C}$ ($10.8 \times 10^{-5}/^{\circ}\text{F}$ to $18 \times 10^{-5}/^{\circ}\text{F}$). Generally, coefficient values reported for materials are single point values and do not reflect the influence of temperature. A typical variation of the thermal expansion coefficient with temperature for a thermoplastic is illustrated in Fig. 4-1. The change with temperature is significant for many engineering products, and data are necessary to analyze properly the effects of dimensional change for plastics in the design configuration.

4-2.2 THERMAL CONDUCTIVITY

Plastics are considered to be thermal insulators, i.e., their heat conductivity is low. This characteristic is beneficial in applications in which heat transfer is not desired, as in insulation, but is detrimental in applications in which low transfer would result in excessive buildup of heat, as would occur in a confined motor housing. Thermal conductivity is a measure of the heat transfer characteristics in terms of the time rate of flow per unit thickness per degree Celsius. The value is useful in simple geometric heat transfer calculations.

Insulative characteristics are of interest for solid plastics but more so for cellular-type plastics. The ASTM has provided appropriate test methods for evaluating plastic materials. For homogeneous materials ASTM Test

Method C177 (Ref. 10) and ASTM Test Method C518 (Ref. 11) have been developed. These two methods use flat specimen shapes of uniform cross section. For other forms and compositions ASTM Test Method C335 (Ref. 12) and ASTM Test Method C236 (Ref. 13) have been developed. Of the four methods ASTM Test Method C177 has traditionally been used to determine the thermal conductivity of plastics. It provides the basic elementary data needed for material comparisons and elementary design calculations.

Due to the existence of much data for plastics gathered by using ASTM Test Method C177, testing for thermal conductivity should be continued with this method. Testing should include

1. Specimen identification, as shown in Table 1-2
2. Common test parameters, as shown in Table 2-4
3. Those parameters unique to the test.

Parameters unique to the test are

1. *Thermal Conductivity.* The average value of thermal conductivity for the specimen under test
2. *Thickness of Specimen.* The thickness of the specimen tested as recommended in the test method
3. *Temperature.* The mean temperature of the test as computed from the temperature gradient of the hot and cold surfaces. Testing shall be performed over a temperature range from 50° to 80°C (122° to 176°F) and at lower or higher temperatures depending on the need.
4. *Relative Humidity.* The relative humidity shall be maintained at 50% where appropriate.
5. *Heat Flux.* The amount of heat applied per unit area through the specimen.

The values of thermal conductivity derived from this procedure represent the steady state flow of heat through the thickness of a specimen. The purpose of these data is to enable comparison of conductivity data for different plastic materials. The data are directly useful in engineering applications in which plastics are used as electrical and thermal barriers (Ref. 14).

4-2.3 SPECIFIC HEAT

Specific heat is a basic thermodynamic property that is a measure of the thermal capacity of a material. It is the quantity of heat required to change the temperature of a unit mass one degree and is expressed in terms of calories per gram per degree Celsius ($\text{cal/g}^{\circ}\text{C}$). The specific heat for the solid state of materials is the one of interest in this handbook. Values for the liquid state are important in polymer processing but do not concern the product designer.

Two ASTM procedures are used to determine specific heat: ASTM Test Method C351 (Ref. 15) and ASTM Test Method D2766 (Ref. 16). Of these two ASTM C351 is the traditional test procedure and is used basically for thermal insulating materials. Specific heat also is determined by thermal analysis, i.e., by DSC (Ref. 17).

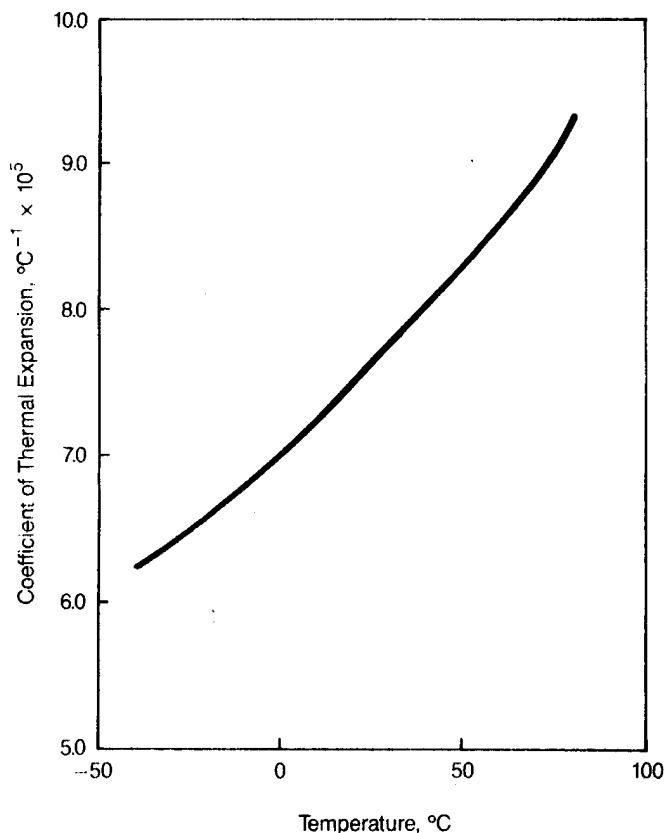


Figure 4-1. Thermal Expansion vs Temperature

Although it is not used for specific heat determinations, ASTM Test Methods D3417 (Ref. 18) and D3418 (Ref. 19) do use the DSC apparatus in thermal assessments. DSC does not give data as accurate as ASTM C351 (Ref. 20), but DSC is a preferred method of obtaining specific heat data because of the simplicity of the test. Appropriate ASTM test methods that use DSC equipment should be modified to incorporate the determination of specific heat for general engineering use.

Testing for specific heat should be performed using differential scanning calorimetry appropriately adapted to an ASTM test method. Also testing should include specimen identification, the common test parameters, and those parameters unique to the test. The data should provide the mean value of the specific heat expressed in cal/g $^{\circ}$ C (Btu/lbm $^{\circ}$ F); 20 $^{\circ}$ C (68 $^{\circ}$ F) is used as the reference temperature.

The heat capacity or specific heat of most plastics is about 0.3 to 0.4 cal/g $^{\circ}$ C, which is numerically identical to Btu/lbm $^{\circ}$ F. The specific heat can be used to compare the thermal capacities of different materials. It is also used for the determination of enthalpy, which is the change in heat content per unit mass from one temperature to another. Enthalpy is used to determine the total heat requirement for the change in temperature for the mass of material.

For ideal materials the values of specific heat in both solid and liquid phases are constants, as shown in Fig. 4-2(A). For plastics the specific heat is a function of temperature, as shown in Fig. 4-2(B). Its value varies little at normal use temperatures, however, but more drastically at and above the glass transition temperature.

Thermal diffusivity is closely related to thermal conductivity and specific heat. By definition it is the ratio of the thermal conductivity to the product of density and specific heat. Diffusivity, expressed in units of centimetres squared per second, is used for heat transfer problems. For plastics, values of thermal diffusivity are on the order of 1.0×10^{-3} cm 2 /s (3.87×10^{-3} ft 2 /h).

4-2.4 MELTING POINT

Melting point is a well recognized and understood property of materials that reflects the transition of a material from the solid to the liquid state. It is also a temperature at which both the liquid and solid states coexist. To a designer, melting point has little direct use; however, it does indicate the ultimate use level for a material. It is important to note that the melting points of those plastics that exhibit a change in state are significantly lower than those of most traditional construction materials.

The melting point is also referred to as the first-order transition; it represents a major change in state. The first-order transition is characterized by the latent heat effect shown in Fig. 4-2(A) or by that point at which the heat content increases at constant temperature.

Melting point for plastics, however, is a misnomer because there is no specific temperature or point for those plastics that have a definable melting condition. Instead the melting occurs over a range and varies significantly with the type of plastic. For highly crystalline thermoplastics the melting point occurs over a very narrow temperature range, i.e., 3 to 5 deg C (5.4 to 9 deg F). For less crystalline thermoplastics the melting occurs over a wider temperature range, i.e., 10 to 20 deg C (18 to 36 deg F).

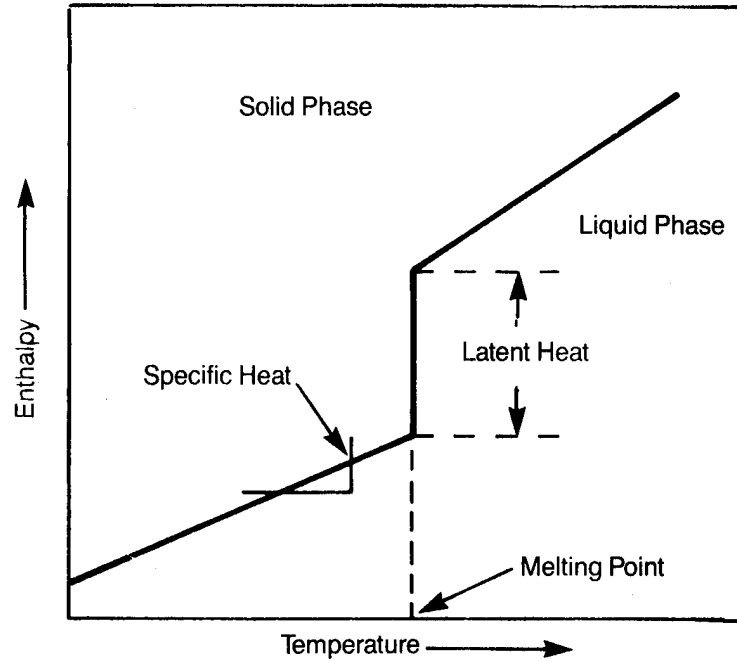
The behavior of crystalline polymers is contrary to that of amorphous thermoplastics and thermosets. Truly amorphous plastics do not exhibit a melting point or range; they exhibit a transition from a soft, rubbery state to a flowable form. On the other hand, thermosets do not melt; they decompose as the temperature is raised. Because of the behavior of amorphous thermoplastics and thermosets, common practice is to report melting points only for crystalline thermoplastics.

Traditionally, the melting point of semicrystalline plastic has been determined by means of a Fischer-Johns melting point apparatus, as listed in ASTM test methods such as D789 (Ref. 21) or by use of a hot stage unit mounted under a microscope, as detailed in ASTM Test Method D2117 (Ref. 22). However, the evolution of thermal analysis has resulted in additional ways to assess the melting point. ASTM Test Methods D3417 (Ref. 18) and D3418 (Ref. 19) provide thermal analysis techniques for determining the first-order transition, and these methods are preferred.

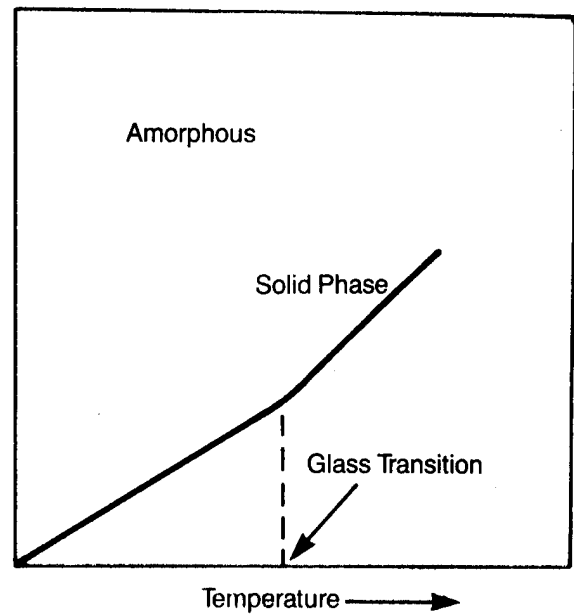
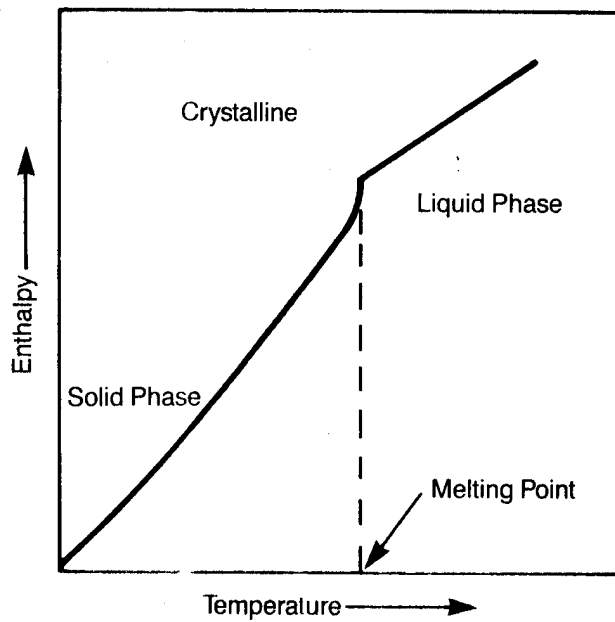
Testing for the melting point should be performed in accordance with ASTM Test Method D3418 (Ref. 19). This method is used to determine other thermal properties, and its use consolidates property determinations. Testing should include

1. Specimen identification, as shown in Table 1-2
2. The common test parameters, as shown in Table 2-4
3. The parameter unique to the test, which is melting point, i.e., the range of temperatures (in degrees Celsius) that indicates the first-order transition for the material. If none can be explicitly determined or decomposition occurs instead, notation should be made.

The melting point range or an indication of the decomposition temperature is a relative measure of the ultimate temperature for use and provides a relative ranking for plastic materials.



(A) Ideal Crystalline Material



(B) Typical Plastic Materials

Figure 4-2. Enthalpy vs Temperature

4-2.5 GLASS TRANSITION TEMPERATURE

Materials undergo molecular changes with changes in temperature. These changes are known as secondary transitions and are characterized by molecular motion within the molecule without the latent heat effects exhibited with the melting point (Refs. 23 and 24). The glass transition is one of the important secondary transitions in design because behavior response can be attributed to change at this temperature. Typically, polymers make a transition, or undergo a change, from glass-like behavior to rubber-like behavior.

This glass transition has traditionally been characterized by a plot of the specific volume of the material as a function of temperature, as shown in Fig. 4-3. When a polymer is heated from below the glass transition point, the volume will increase with temperature at a constant rate. As heating continues, a point is reached at which the rate of volume increase will abruptly change due to a change in molecular mobility. This point is defined as the glass transition temperature T_g . It is at this temperature that a polymer loses its rigidity, or glassy behavior, and takes on a rubbery or leathery behavior due to large molecular motions. Most materials, both amorphous and crystalline, exhibit second-order transitions; the values of which vary widely with the type of plastic. T_g values, which may range from below -100°C (-148°F) to above 100°C (212°F), are used to explain the changes in mechanical, electrical, and thermal behavior encountered in plastic evaluations.

Experimental techniques have determined the existence of other secondary transition temperatures referred to as β and γ transitions. These transitions are generally investigated by polymer scientists in order to explain fundamental material characteristics, but the role of these transitions in behavioral response is not as important as the glass transition T_g .

The glass transition temperature for materials has been analyzed by using a number of mechanical and thermal techniques; thermal analysis is a more rapid means of

testing. The equipment for both DTA and DSC are specified to measure T_g in accordance with ASTM Test Method D3418 (Ref. 19). The ASTM test procedure also enables determination of other detectable second-order transitions and the melting temperature.

Testing for T_g must be performed in accordance with ASTM D3418 and should include

1. Specimen identification
2. Common test parameters
3. Those parameters unique to the test.

Parameters unique to the test are

1. *Glass Transition Temperature.* The temperature of the glass transition T_g in degrees Celsius
2. *Rate of Heating.* The average rate of linear temperature change in degrees Celsius per minute.

The glass transition temperature, which is indicative of a change from a brittle-like response to a rubber-like response, is useful in anticipating end use behavior, e.g., impact behavior. A comparison of the T_g with the functional use temperature range will provide insight into anticipated problems or will indicate a need for additional performance testing. Also the T_g has been quite useful in failure analysis to explain cause and effect.

4-3 THERMAL DECOMPOSITION

When plastic materials are subjected to ever-increasing temperatures, thermal decomposition will occur and will culminate for many materials in burning or pyrolysis. This decomposition process begins prior to burning in the form of emitted vapors caused by chemical breakdown and/or vaporization of constituent compounds. Decomposition is rapidly accelerated in the burning process, which generates heat and smoke and results in emissions of toxic gases and vapors.

Costly industrial fires have caused increased interest in thermal decomposition initiated by the fire environment. Similar concerns exist in armed conflicts because destructive fires can result from the use of incendiaries and highly combustible fuels (Ref. 25).

Because plastics are organic compounds, they will deteriorate under high heat and may combine with other compounds to produce harmful effects. In a high-heat environment, however, they represent primarily a fire risk when not properly used. The degradation process will vary with the plastic structure. In general, most thermoplastics will melt and eventually be destroyed by burning, whereas thermosets decompose by charring. Some plastics are difficult to ignite, and some will stop burning when an impinging flame is removed, whereas others will not (Ref. 26). In other words, the response is quite varied for the many available plastics.

Continuing materials research is concentrated on the fact that the burning characteristics of plastics are commonly altered by the use of flame-retardant treatments or additives. Although necessary for fire suppression,

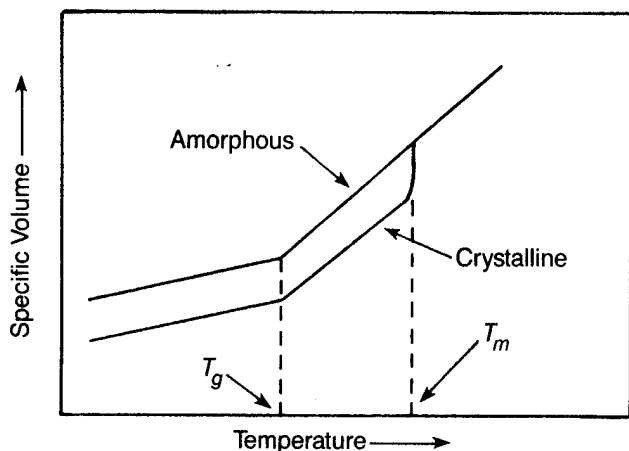


Figure 4-3. Specific Volume vs Temperature

sion, the use of fire retardants should raise questions about their influence on plastic behavior including whether the additives contribute to toxicity (Ref. 27). Additives may affect chemical and ultraviolet resistance, mechanical properties, cost, and even processing (Ref. 28). Thus in designing with plastics flame retardants should not be used without considering how they may influence material performance.

Thermal decomposition as defined in this handbook encompasses a group of properties that are the principal result of burning. The terms normally associated with decomposition are flammability, smoke generation, and thermal gas, or vapor, emission. Flammability has traditionally described the ignition and burning characteristics of materials. Smoke generation and gas, or vapor, emissions are direct results of the burning process. These properties have been controversial. In particular, comparison of laboratory test data to real fire situations has raised questions about the methods used to obtain and the interpretation of the laboratory data. These questions are discussed in the paragraphs that follow.

Ablation is another form of thermal decomposition of interest for military use of plastics. It has application in missile nose cones, rocket nozzles, and other very high-temperature technology areas, i.e., where the extreme temperature causes a gradual loss, or erosion, of material. Ablative materials are thermally protective and are generally composed of thermosetting plastics with inorganic reinforcements. Because the ablative response is considered a special use property that should not be evaluated in general testing, it is not discussed in this handbook.

4-3.1 FLAMMABILITY

Flammability is an all-encompassing term that is sometimes used to describe the process of burning and the emission of smoke and toxic gases. As defined by the American Society of Testing and Materials in Ref. 29, flammability refers to the ease of ignition and relative ability to sustain burning and includes self-extinguishing and smoldering characteristics.

One of the most controversial aspects of flammability is measurement because small-scale laboratory testing does not reflect the response that occurs in real, large-fire environments. Many industrial, governmental, building code, and testing organizations are actively assessing test methods and materials technology to make possible the prediction and evaluation of the effects of burning on plastic materials and the development of standards for consumer use.

The effort directed at flammability is manifested in the 14 test methods (Refs. 30 through 43) promulgated by ASTM over many years. Each method addresses determination of the ignition and/or burning characteristics of various materials. Of the 14 test methods, seven (Refs. 30

through 36) are devoted to plastic materials in various forms and/or conditions of test. The other seven (Refs. 37 through 43) are associated with building codes, aerospace applications, or electrical insulating materials. These methods are mostly large-scale burn tests that are not unique to plastics.

In most testing for flammability, a flame is applied to the material and the burning characteristics are observed. Although other means, such as radiant energy, hot air, and electrical discharges are available to initiate combustion, flame initiation is of the greatest interest.

Testing for the flammability of plastics focuses on the burning rate of the material. Associated with this property are ease of ignition, flame spread or extinction, dripping, and smoldering. All of these secondary characteristics are of interest in any burning rate test.

Most laboratory test procedures are not useful as fire-hazard tests because they are small-scale tests (small specimens) and do not duplicate the intensity generated in real fire environments. On the other hand, large-scale tests that might duplicate real fire environments are not practical to evaluate burning rates for the many plastic materials. This dilemma is best addressed by determining the general burning characteristics in small-scale tests and evaluating large fire situations on an as-needed basis. The laboratory test should be used only as a screening mechanism in the material selection process.

In all testing for material properties, the ASTM procedures are generally preferred. Although industry-type tests (Ref. 44) are used, they offer no significant advantage over the ASTM procedures. Of the ASTM test methods for plastics, D635 (Ref. 30) is the principal procedure used to determine burning rate. However, industry has made wide use of Underwriters Laboratories (UL) Standard UL94 (Ref. 44) as a basis for classifying the flammability of plastic materials. These two test methods, ASTM D635 and UL94, are the source of most reported flammability data.

ASTM D635 is a small-scale laboratory test used to compare the flammability characteristics of self-supporting, solid-type plastics. It was developed for plastics that support their own weight in the specified thickness range. The method, which involves testing the specimen in the horizontal position, is used to determine the average burning rate, average time of burning, and average extent of burning. Those materials not considered self-supporting are evaluated by test methods that position the specimen vertically.

UL Standard UL94 is commonly used in industry to assess the flammability of plastics. Like ASTM D635, it is a small-scale laboratory test intended to be a preliminary indication of the flammability of the particular plastic. UL94 ratings generally apply to materials used for parts in electrical devices and appliances. The test procedure classifies the flammability of plastics, including foams

and thin films, in a horizontal and/or vertical position. The UL94 classification is designated by symbols that denote a maximum burning time, maximum glow time, and dripping characteristics.

The UL94 standard is preferred by industry because it employs a vertical position for burning, a condition not used in ASTM D635. It also provides a semiquantitative classification system; it does not specify burning rates. One disadvantage, however, is that unless an individual is quite familiar with the test procedure, the classification designation has little direct meaning. Of the two laboratory test procedures, ASTM D635 is considered to be better suited for indicating the relative flammability of plastics. If all supporting data are provided, a specific burning rate or time of burning has more practical value for comparing materials. The main disadvantage of ASTM D635 is that a vertical position for burning is not specified. To overcome this limitation, ASTM has developed a test method, D3801 (Ref. 31), that incorporates the vertical test procedure as performed in UL94. When ASTMs D635 and D3801 are both used to evaluate materials, they provide an effective assessment of flammability.

In addition to ASTMs D635 and D3801, five other ASTM test methods have been developed. Of these five, only Method D568 (Ref. 32) is a rate-of-burning test comparable to ASTM D635 and is useful in assessing flammability. It was developed specifically for thin sheeting or film and differs from ASTM D635 in that the position for burning is vertical.

The remaining four ASTM test methods (Refs. 33 through 36) are useful for special purposes but should not be imposed on all solid-type plastic materials as covered in this handbook. ASTM D3713 (Ref. 33) is a burn-type test for solid plastics during which a flame is applied and removed incrementally, and measurement of response is made accordingly. This is a special type of flame ignition test, and it has no significant advantage over ASTM D635.

ASTMs D3014 (Ref. 34) and D3894 (Ref. 35) apply to the burning of cellular plastics, which are not covered in this handbook. One test method, D2863 (Ref. 36), measures the minimum oxygen concentration required to support combustion and is useful in materials research.

Flammability testing should be conducted in accordance with ASTMs D635 (Ref. 30) and D3801 (Ref. 31). The burning characteristics of plastics are thickness dependent; therefore, it may be necessary to use ASTM D568 (Ref. 32) to supplement D635 and D3801. Both test procedures should include specimen identification and the common test parameters in addition to those parameters unique to the test, which are

1. *Burning Rate.* The average burning rate, in cm/min (in./min), for all specimens that have burned to a 100-mm (3.94-in.) mark on the specimens

2. *Time of Burning.* The average time of burning, in

seconds, for those specimens that did not burn to a 100-mm (3.94-in.) mark on the specimens

3. *Extent of Burning.* The average distance the specimens burned, in mm (in.), for those specimens that did not burn to a 100-mm (3.94-in.) mark on the specimens

4. *Thickness.* The thickness of the specimen, in mm (in.), which should be 3.2, 6.4, and 12.7 mm (0.126, 0.25 and 0.5 in.). Testing is desired at 1.6 mm (0.06 in.) and lower, as appropriate for the material under test.

5. *Test Position.* The position of the specimen, horizontal or vertical, for the test conducted. Both test positions are preferred for all testing.

6. *Visual Observation.* Any qualitative observation made during the test to indicate dripping, flowing, or falling burned particles.

For the various plastics measured in accordance with ASTMs D635 and D3801, the test results indicate the relative flammability characteristics in quantitative terms. The tests reflect whether the material will propagate a flame when ignited and the flame source is subsequently removed. The time and extent of burning indicate the relative degrees of propagation and extinction. In essence, the tests indicate those materials that will burn readily and those that will not.

ASTMs D635 and D3801 differ in that they are horizontal and vertical tests, respectively. They also differ in that in the D635 test the burner is applied for 30 s and is removed, whereas in the D3801 test the burner is applied for 10 s, removed, and placed under the specimen for another 10 s if flaming ceases. These two ASTM tests complement each other.

The laboratory test procedures do not indicate decomposition in any other environment, i.e., ambient oxygen, no draft, and ambient temperature. Therefore, actual fire tests under anticipated conditions should be performed as appropriate.

4-3.2 SMOKE DENSITY

Experience with fires involving plastics has indicated that smoke generation from burning or smoldering materials directly affects human lives (Ref. 45). The particulate matter produced is a tacky, oily aggregate of carbon particles with absorbed combustion products. Smoke particles are hazardous because they produce toxic effects by inhalation, they inhibit occupant escape from a burning structure, and they impede rescue and fire control. Smoke hazards have attracted enough attention that material research efforts are being directed at minimizing smoke generation. Therefore, the designer should consider the relative amount of smoke generated by burning plastics when the potential of fire exists.

In testing for the amount of smoke produced, the result is generally expressed as a numerical value. Unfortunately, such laboratory data have not been correlated with data from actual fires and validated. Until this gap in

technology has been filled, laboratory methods must be used to ascertain a relative value for plastic materials.

A number of laboratory test methods have been developed to measure the smoke generated by materials (Ref. 45). Tests, performed in confined chambers with appropriate ventilation, use either an optical or gravimetric means of measurement for smoke. The optical method measures the degree of obscuration produced by smoke, whereas the gravimetric method measures the percent of material burned (by the collection of smoke particles). Of the two types, the optical method is believed to provide a more practical means of assessing relative material performance for design use. Also for plastics that exhibit melting and smoldering characteristics, the calculation of smoke based on weight loss may be invalid in material comparisons (Ref. 46).

Four smoke tests were developed over the years, and some controversy remains as to which is the most suitable for use with all materials. Two of the test methods are ASTM E84 (Ref. 38) and D2843 (Ref. 47). The other two are the National Institute of Standards and Technology (NIST)* Smoke Test and the Ohio State University (OSU) Release Rate Test. The NIST Smoke Test has been promulgated as ASTM E662 (Ref. 48).

Of the four laboratory test methods, the former NIST Smoke Test (now ASTM E662) appears to be the most suitable for plastic materials. It overcomes the criticism of ASTM D2843 (developed for plastics) that stratification of smoke in the horizontal chamber could occur (Ref. 46). Correlation of data between ASTM E662 and D2843 is reasonably good in some cases and relatively poor in others (Ref. 49). ASTM E662 is believed to be the more useful method, and modification has been suggested to improve the test procedure (Ref. 50).

Of the other test methods previously noted, ASTM E84 (Ref. 38) is inappropriate for laboratory testing because of the size and expense of the test chamber. The OSU Release Rate Test has the advantage of greater flexibility in testing (Ref. 46) and has been developed into ASTM Method E906 (Ref. 51).

Of the available laboratory test methods, ASTM E662 (Ref. 48) is the preferred method for measuring the smoke generation of solid plastics. Testing should include the specimen identification, the common test parameters, and those parameters unique to the test such as

1. *Specific Optical Density.* The dimensionless optical density of smoke evolved; this value is calculated from the light transmittance. The maximum value is to be noted accordingly, i.e., the point at which light transmittance is a minimum.

2. *Time.* The value, in minutes, for each measurement of light transmittance. Testing should be conducted for a minimum of 20 min.

3. *Exposure Type.* Tests should be performed under both the flaming and nonflaming (smoldering) conditions.

4. *Thickness of Specimen.* Testing should be performed at thicknesses of 3.2, 6.4, 12.7, and 25.4 mm (0.126, 0.25, 0.5, and 1 in.).

The specific optical density calculated from this test provides a relative measure of smoke generated by burning or smoldering plastics. The calculation is based on a measurement of light obscuration, in terms of light transmission, caused by generated smoke. The test does not associate the physiological reactions of human beings to eye irritants and toxicity. Also the results represent only the smoke emitted under the specific test condition and have not been correlated with other test methods or actual fire situations. The results may be used to screen materials if high priority is given to fire situations or to heighten the awareness of the need to cope with emitted smoke in the event of fire.

The specific optical density will vary with time as the smoke builds up from its initial point of generation as shown in Fig. 4-4. It will reach a maximum, which is identified as the maximum specific optical density. Also the test results provide an indication of the rate of smoke generation, which is a function of specimen thickness. As the thickness of the specimen increases, the maximum specific optical density also increases, as shown in Fig. 4-5, but not linearly. This nonlinearity is due to a decreasing burning rate as the burning layer progresses into the specimen and to other smoke generation phenomena.

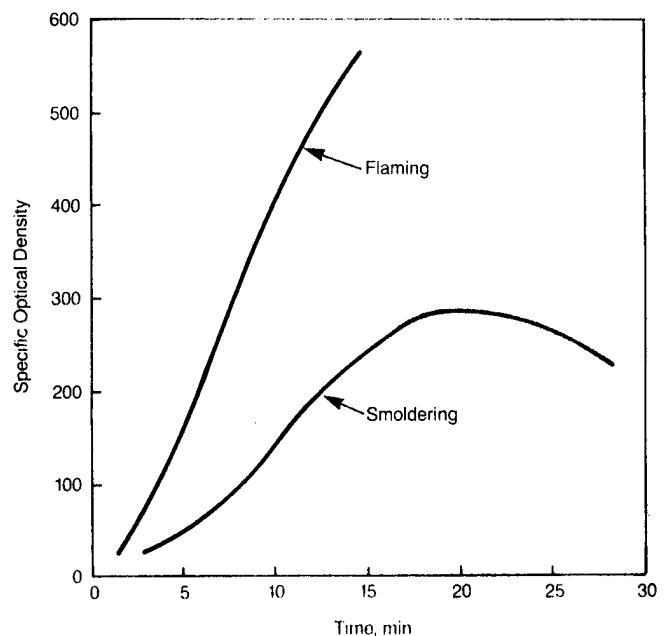


Figure 4-4. Specific Optical Density vs Time

*Formerly the National Bureau of Standards

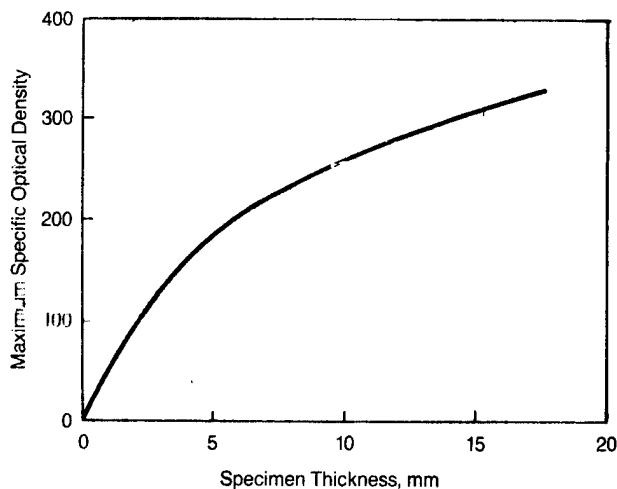


Figure 4-5. Maximum Specific Optical Density vs Thickness

4.3.3 THERMAL GAS EMISSION

As is the case with smoke, the gaseous emissions from a fire situation present a serious hazard to life. Harmful physiological responses are due to either vapor inhalation or skin contact. Gas emissions from plastics occur not only in a fire environment but also during the heating of a plastic because degradation occurs without ignition. In general, however, more attention has been given to the fire environment.

Although plastics emit toxic gases, so do the traditional materials of construction, and these are not considered to be safer than plastics (Refs. 5 and 6). This observation is based on the limited available knowledge concerning the time element of gas generation within a fire.

Although serious, the hazard caused by the evolution of toxic gases during the early stages of a fire is not as great as it is in later stages. As a fire develops, toxicity hazards occur that are common to all fires regardless of the materials being consumed, i.e., excess carbon monoxide and carbon dioxide or the deficiency of oxygen. The toxicity of plastic combustion products is a hazard within the fire environment and in the surrounding area in the form of atmospheric contaminants and corrosive vapors.

The principal toxic combustion product is carbon monoxide. However, lesser concentrations of the more noxious gases such as hydrogen chloride, sulfur dioxide, and hydrogen cyanide are present by themselves or in conjunction with the typical combustion products.

Determination of the toxic gases produced during the burning of specific polymers is complex because there are many test variables, which include ignition source, ventilation (presence of oxidizer), temperature, change in material form (melting), duration of heat application, size of fire enclosure, completeness of combustion, and the interdependence of such factors. Due to these factors, no meaningful, uniform laboratory test procedure is believed

to be available. Researchers have determined the gases emitted from most plastics (Refs. 52 and 53), but their results may have little relation to real fire environments.

A standard test method must be developed that will determine the products of combustion of plastic materials. Although a laboratory test does not reflect all possible fire environments, it does provide some basic information with which to assess cause and effect. Testing should also consider the evolution of gases that takes place during the thermal degradation process for plastics but prior to initiation of combustion. This evaluation would provide valuable information regarding the use of plastic materials in confined, high-temperature areas.

Much of the plastic materials research has concentrated on the use of additives to improve processing, weatherability, thermal stability, and flammability. These additives constitute a wide variety of chemical compounds that, by themselves, may present a toxic emission problem that previously did not exist. This possibility necessitates that testing of plastics be directed at the specific material identified by a trade designation and not the generic form.

The promulgation of a laboratory test procedure should include the specimen identification, the common test parameters, and those parameters unique to the test such as

1. *Products of Combustion.* The chemical compounds emitted under the conditions of test. Data for emissions prior to and after the generation of a flame are desirable.

2. *Concentration.* The concentration of the gases emitted in parts per million per unit weight of the material.

The availability of data for gases emitted due to thermal degradation will enable designers to assess the impact on personnel. Also evolved gases such as chlorine may react with moisture or other compounds to cause deterioration of materials or unexpected personnel responses.

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CHAPTER 5

ELECTRICAL PROPERTIES

Electrical properties are introduced by discussing the nonconductive nature of plastics, their industrial importance, and the influence of end use environments. The electrical properties discussed include the dielectric properties and electrical resistance.

5-1 INTRODUCTION

Plastic materials are well recognized for their excellent electrical insulating, or dielectric, properties (Ref. 1) and thus are widely used in industry. Although their electrical characteristics are based on chemical composition and structure, not all plastic materials are totally inert electrically because plastic materials have been developed with alteration to their nonconductive nature. Conductivity is accomplished with carbon black, metallic additives, and other compounds for special applications, such as anti-static use. More recently, conductive polymers have been developed that do not rely on additives.

The nonconductive nature of plastics was an early impetus in the development of plastic materials for both electrical power and electronic applications. The prime function of plastics for power applications was as an insulator (or dielectric) used to separate high-voltage, current-carrying conductors from regions of lower voltage. Plastics were also developed for use as the dielectric of a capacitor.

One way to differentiate insulative and conductive materials is in terms of the volume resistivity, as noted in Table 5-1.

TABLE 5-1
CLASSIFICATION OF CONDUCTIVE
MATERIALS (Ref. 2)

VOLUME RESISTIVITY, ($\Omega \cdot m$)	CLASSIFICATION
0-10	Conductor
10-10 ⁶	Partial (Semi-) Conductor
10 ⁶ -10 ¹⁶	Insulator

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Thus an insulator is a material having high resistivity, i.e., a value of greater than 10⁶ $\Omega \cdot m$. The classes listed in Table 5-1 are arbitrary and may overlap depending on the environmental condition of the material.

The electrical properties used in design are those well established by the American Society for Testing and Materials (ASTM) test procedures. The uses of plastics in

electrical and electronic applications are significantly affected by the environment, which includes electrical stress and atmospheric conditions. The most significant stress factors are the voltage, amperage, and the associated frequency. The most significant environmental factors are temperature and humidity. These factors form the prime variables in all basic testing. Other factors such as general aging, heat aging, and moisture content may also significantly affect results and should be considered accordingly in testing, although they are not discussed in this chapter.

The variety of industrial applications results in a wide range of electrical conditions. Voltage may vary from a fraction of a volt to millions of volts in power generating systems. Current, or amperage, ranges from microamperes to millions of amperes. Alternating fields encompass frequency ranges from zero or direct current (dc) to 60 Hz (power frequencies) and all other alternating currents (ac) of frequencies to 10¹⁰ Hz.

For dielectric applications an insulator is also required to provide mechanical support for the current-carrying conductor. Therefore, material selection is normally conducted by jointly considering electrical and mechanical properties as well as thermal properties and environmental factors.

Because many materials may be used to meet specific application requirements, the material selection process is complicated and places great emphasis on material property data.

The electrical properties of primary interest and those most widely reported in the literature are dielectric strength, ac loss characteristics, and resistivities. Less attention is given to arc resistance and the phenomenon of corona.

Testing for electrical properties generally emphasizes frequency, temperature, and moisture dependence. Other factors not considered in this chapter, but that do affect these properties, are the many special environmental effects. Also not considered are the anisotropic behavior of materials and the test methods themselves, which may influence the results. Electrical properties may vary due to the anisotropy of the material, i.e., directional properties. When a material exhibits dielectric anisotropy, the fact is

normally stated in the specimen identification, as shown in Table 1-2. All of these factors complicate the generation of effective engineering data.

5-2 DIELECTRIC STRENGTH

This electrical property represents the ability, or strength, of a dielectric material to withstand a voltage on it. In other words, it is a measure of the voltage necessary to cause dielectric breakdown or to effect a spark discharge. As shown in Fig. 5-1, a voltage is applied to one side of the material and is raised until the material is punctured by a spark discharge. This property is described as dielectric strength.

Dielectric strength is associated primarily with power frequencies and is measured, in accordance with ASTM D149 (Ref. 3), in terms of a voltage gradient. The value is determined by dividing the breakdown voltage by the thickness of the specimen and is generally expressed in kilovolts per millimetre (volts per mil) of thickness. Values of dielectric strength may vary from a high of 39.4 kV/mm (1000 V/mil) to a low of 0.039 kV/mm (1V/mil). The higher the value, the better the insulator. Those materials that conduct electricity do not have a value. For testing of polymeric films ASTM D2305 (Ref. 4) is specified. Ref. 4, however, refers to ASTM D149 (Ref. 3) for the actual testing procedure.

Even though in actual application the frequency of the applied voltage may vary, most tests are done with a source of 60 Hz. This represents the frequency used in commercial power generation and distribution. The dielectric strength may vary with other frequencies, but testing at these frequencies is considered to be a special requirement. Although testing is performed at other frequencies, the test at 60 Hz is more severe and usually yields more conservative values.

The significant variables in this test to determine dielectric strength are the applied voltage, specimen configuration, temperature, and the preconditioning procedures. Because of the many variables, the data cannot be applied directly to field use unless all conditions are the same. Because dielectric strength varies considerably with insulation thickness, specimen thickness is important.

The dielectric strength testing—conventionally performed in accordance with ASTM D149 (Ref. 3)—allows for three methods of applying the voltage: (1) short time, (2) slow rate of rise, and (3) step-by-step.

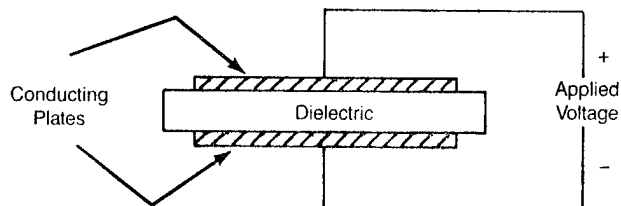


Figure 5-1. Dielectric Strength Schematic

The short-time test should be used to evaluate the influence of thickness and temperature on the dielectric strength, whereas the step-by-step method should be used to evaluate the time to failure at different voltages. This evaluation is accomplished by applying voltages from 50% of the short-time test value in slow steps. Similarly, the slow-rate-of-rise test is performed at an initial voltage of 50% of the short-time test value to give the test specimen approximately the same voltage-time exposure as provided in the step-by-step test but at a uniform rate.

In all testing the breakdown voltage is quite sensitive to material inhomogeneity. These irregularities include cracks, fissures, voids, impurities, and laminar defects, and all testing assumes materials are free of these imperfections. The short-time test, however, may not detect their influence, and even the step-by-step test may not reveal their full detrimental effects on the dielectric strength. Thus end use testing is always recommended to assure performance.

Testing for dielectric strength should include specimen identification parameters described in Table 1-2, the common test parameters described in Table 2-4, and those parameters unique to the test. These unique parameters are

1. *Dielectric Strength.* The average dielectric strength and the standard deviation are calculated from breakdown voltage measurements in terms of kV/mm (V/mil). Dielectric strength is desired for various thicknesses at standard temperature and humidity conditions and for various temperatures at constant thickness.

2. *Applied Voltage.* The short-time test should use a voltage rate of rise of 500 V/s. The source should be 50-60 Hz with a sinusoidal waveform. For the test at constant voltage the breakdown voltage should be at four increments from the maximum down to a value that is 50% of the breakdown voltage.

3. *Surrounding Medium.* All testing should be performed in air. Testing with other gases is considered a special condition.

4. *Temperature.* Testing should be performed at the standard and the high temperatures, as indicated in Table 2-4, and should use the nominal specimen thickness of 3.18 mm (0.125 in.) and the nominal relative humidity of 50%.

5. *Specimen Thickness.* The nominal specimen thickness for all tests is 3.18 mm (0.125 in.). For tests to determine the influence of thickness 1.6, 0.8, 0.4, and 0.2 mm (0.063, 0.031, 0.016, and 0.008 in.) should also be used.

6. *Electrodes.* The preferred electrodes are the opposing cylinders of 51 mm (2.0 in.) in diameter with 6.4-mm (0.25-in.) radius edges, Electrode, Type 1, as listed in ASTM D149 (Ref. 3).

7. *Relative Humidity.* The testing environment should be the standard 50% relative humidity.

8. *Time.* The time to failure is measured in hours for the applied constant voltage from the maximum dielectric strength to a value of 50% of the maximum.

The dielectric strength can be used as a relative measure of material performance and to determine whether a material merits further consideration. Generally, further testing is necessary for the specific end use conditions either in the laboratory test configuration or in final product configuration.

With respect to specimen configuration, thickness is the variable of greatest interest. Data for dielectric strength as a function of thickness are illustrated in Fig. 5-2. This relationship is typical of many materials and indicates the generally higher values in thin sections, as found in films. Other geometric and material variables include shape, area, homogeneity, directionality, and imperfections. All of these factors influence dielectric strength and should be considered in end use evaluations.

Dielectric strength of most plastics decreases with an increase in temperature; this relationship is illustrated for a typical plastic in Fig. 5-3. The influence of temperature is the result of a combination of a change in material structure with increased temperature along with the heating effect that results from the applied voltage.

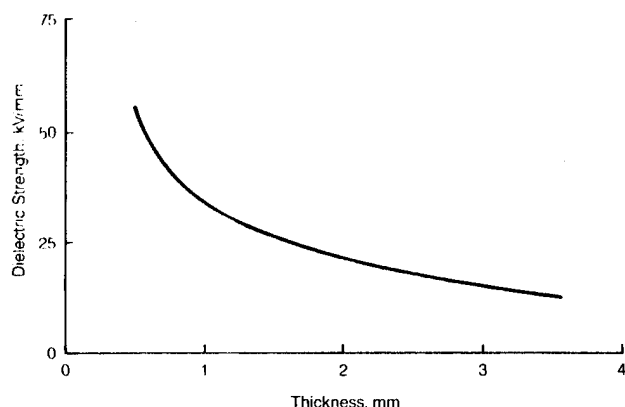


Figure 5-2. Dielectric Strength vs Thickness

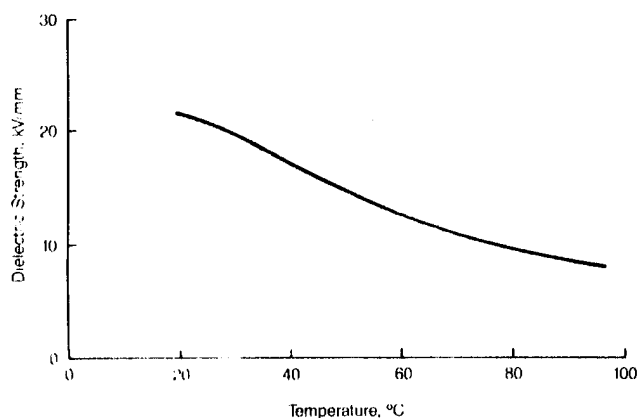


Figure 5-3. Dielectric Strength vs Temperature

The influence of humidity on dielectric strength has been limited to testing of a material in a surrounding medium of air at a relative humidity of 50%. Although high humidity has an effect on some plastics, the effect is due primarily to water vapor absorption by that material. Thus those materials known to absorb water should be evaluated after conditioning at high and low humidity.

5-3 PERMITTIVITY (DIELECTRIC CONSTANT)

The permittivity, or dielectric constant, of a material is a measure of its capacitance, i.e., or the ability to store an electrical charge. Fundamentally, capacitance is defined as the ratio of the quantity of charge that can be stored at its surface divided by the voltage potential. Generally, the measurement for dielectric constant is made in terms of capacitance and is relative to a vacuum by removing the dielectric or dry air, which has a dielectric constant of unity, as shown in the schematic in Fig. 5-4. The dielectric constant is defined as the ratio of the capacitance of the material to the capacitance of a perfect dielectric or a vacuum.

Although the term "dielectric constant" is widely used, the preferred term is "permittivity" (Refs. 5 and 6), or more so the "relative permittivity", which conforms to international usage. The term "dielectric constant" is truly a misnomer because for any material it is a constant within a limited set of conditions. The term "specific inductive capacity" (SIC) has also been used to describe this property but is not widely used.

In an alternating current electrostatic field, the permittivity is greatly influenced by the broad range of frequencies. This influence is due to the polymer structure and its electronic polarizability. If an alternating voltage is applied, it is necessary for the polarization to reverse each time the polarity of the field changes. This frequency dependence is also related to material composition, e.g., fillers or impurities, and other external environments, particularly temperature.

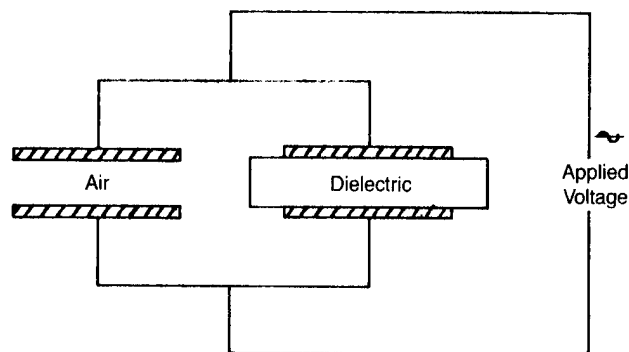


Figure 5-4. Permittivity (Dielectric Constant) Schematic

Testing for permittivity should include specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test. These unique parameters are

1. *Permittivity*. The average value of permittivity for each condition of test

2. *Frequency*. The frequency range should include all frequency decades from 10^{-6} Hz to 10^{12} Hz.

3. *Temperature*. The test temperature should range, as suggested in Table 2-4, from -55° to 70° C (-67° to 158° F) or to higher temperatures as appropriate for the material.

formed at a relative humidity of 50%.

5. *Measurement Method*. The method of measurement is dictated by the appropriate frequency range of the test.

6. *Electrode*. The preferred electrode system is the guarded type, i.e., three-terminal, as specified in ASTM D150 (Ref. 5).

7. *Applied Voltage*. The voltage applied to the specimen is a function of the test conditions.

The range of permittivities for plastics is generally from 2 to 10; some materials exceed the upper limit. These values are based on a comparison with air, which has a value of 1.

The low values are best for high-frequency or power applications to limit electric power loss. These applications are primarily insulative. The high value of permittivity is desired for capacitance applications to allow a capacitor of small physical size. Materials with intermediate ranges of permittivity are of value to minimize

corona, gradient stresses at conductor edges, and to attenuate high-frequency power.

The permittivity varies as a function of frequency, as shown on Fig. 5-5. Although common practice is to report permittivity at specific frequencies, such as 60 Hz, 1 KHz, and 1 MHz, for engineering use it is necessary that the full range be provided. Generally, the variation in permittivity with frequency is the result of molecular polarization, which, in essence, is an effect that varies with each polymeric material.

Temperature also has a pronounced effect on permittivity, as shown in Fig. 5-6. This effect is due to the smaller or greater molecular activity, or mobility, which results at the lower or higher temperatures, respectively. Generally, the high temperatures will have a more pronounced effect, particularly with polar materials. Testing over a broad range of temperatures and frequencies can result in a graphical presentation in the form of contour maps, as shown in Fig. 5-7.

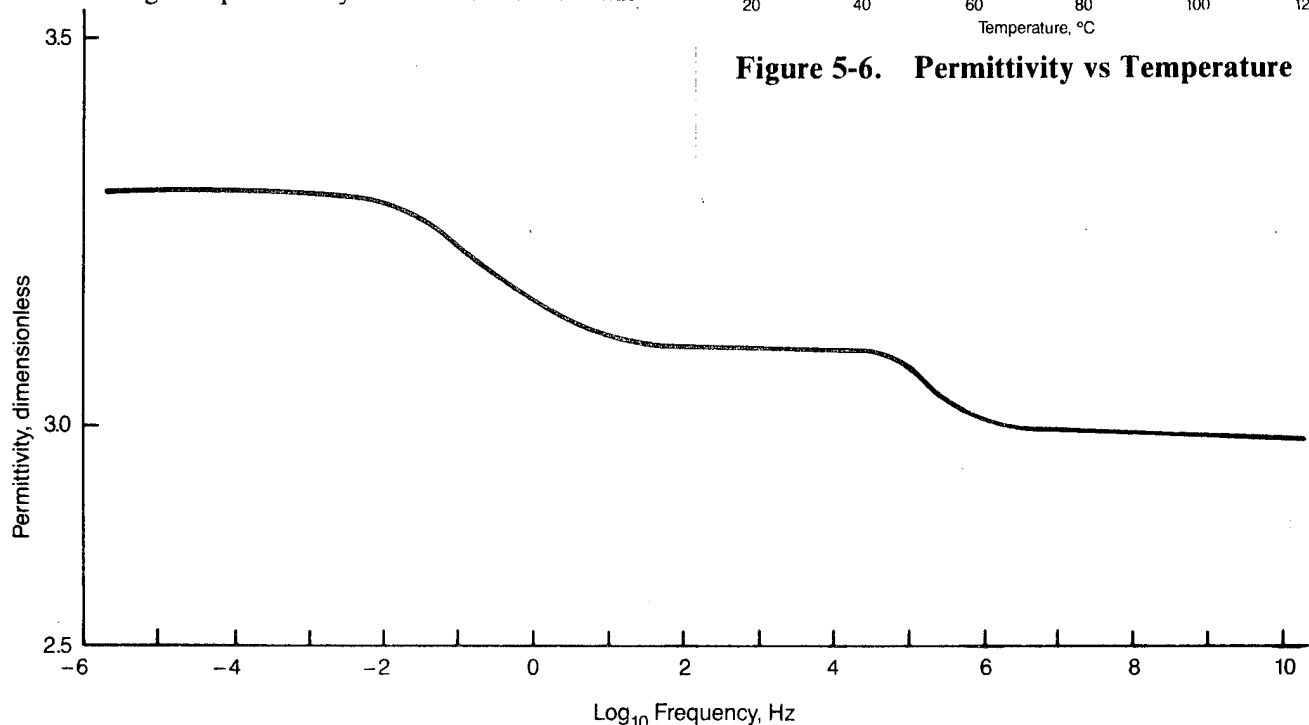


Figure 5-5. Permittivity vs Frequency

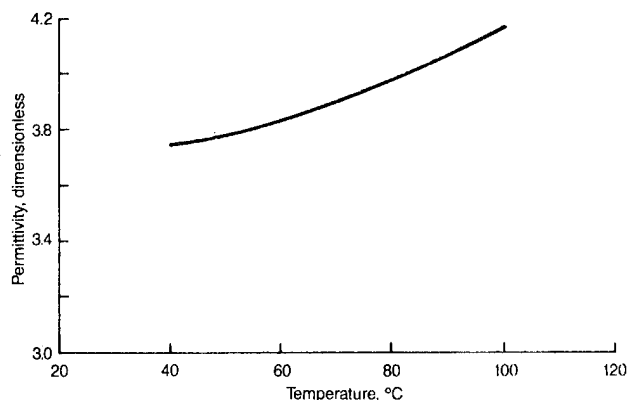
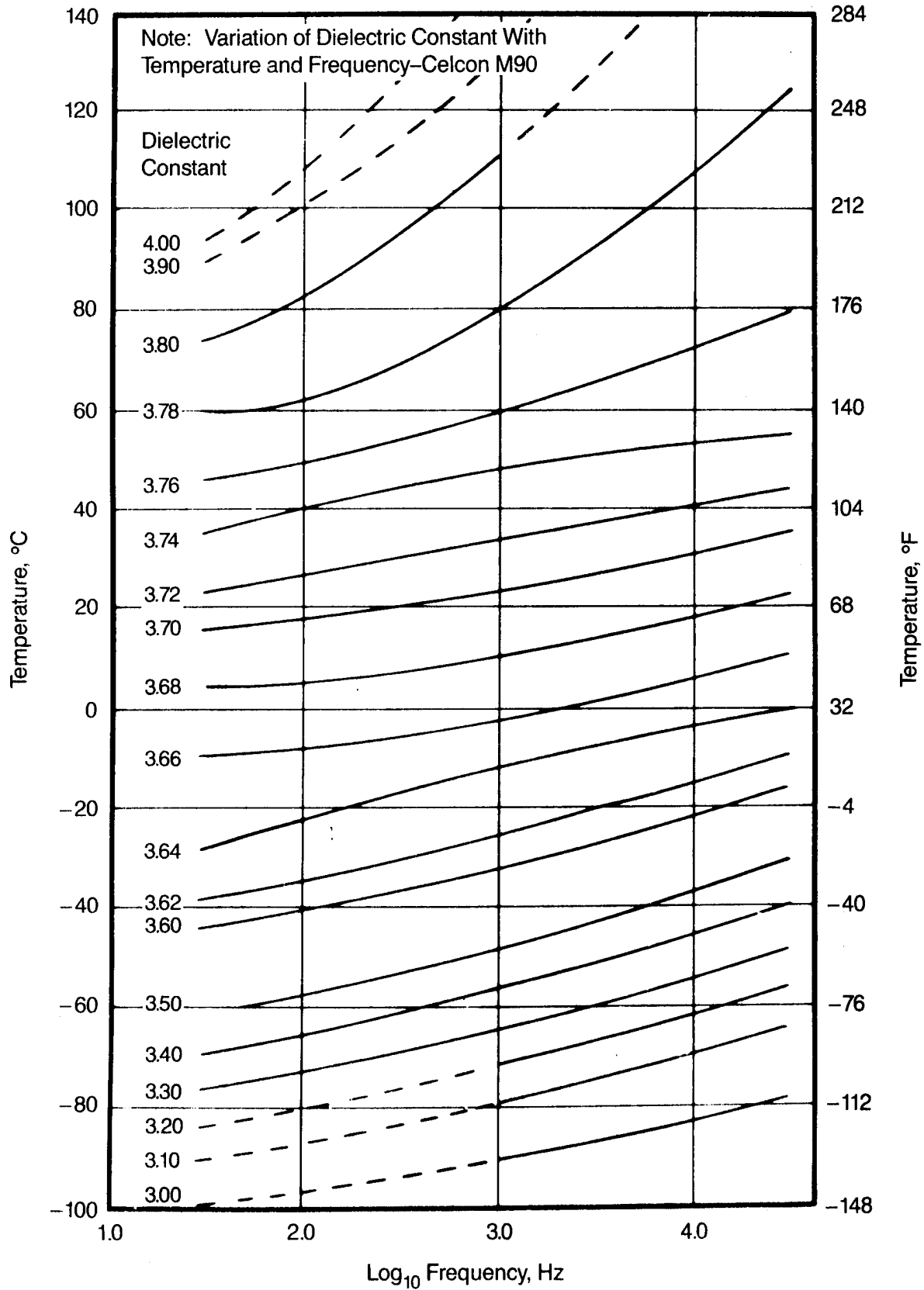


Figure 5-6. Permittivity vs Temperature

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From CELCON Design Manual, Celanese Corporation, Celanese Engineering Resins, Summit, N.J.

Figure 5-7. Permittivity vs Frequency and Temperature

5-4 DIELECTRIC LOSS CHARACTERISTICS

As a dielectric is subjected to the buildup and collapse of an alternating current field, it encounters a resistance that is manifested in the dissipation of electrical energy, which is in the form of heat. This heat is the result of the frictional resistance caused by the change in polarity within the polymer structure. This loss is measured primarily in terms of the dissipation factor. Other terms indicative of an electrical loss are the power factor and loss index, which are discussed in the paragraphs that follow.

5-4.1 DISSIPATION FACTOR

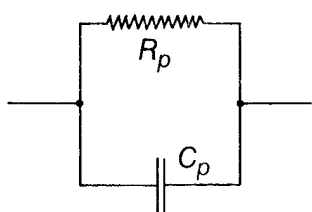
The dissipation factor, also known as the loss tangent (Refs. 5 and 7), is defined as the tangent of the dielectric loss angle or the cotangent of the phase angle. Although

the parallel circuit is a more proper representation of a dielectric material, the dissipation factor of the capacitor is the same for both the series and parallel representations shown in Fig. 5-8.

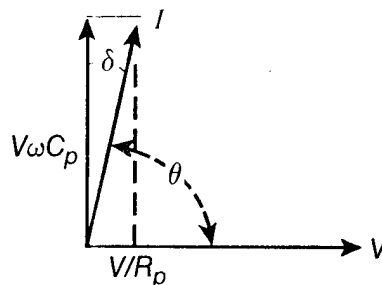
For a perfect capacitor the dielectric phase angle between voltage and current is 90 deg. Because no dielectric is perfect, the phase angle will always be less than 90 deg and some energy is always dissipated and is not recoverable.

Regarding permittivity, the dissipation factor is greatly influenced by frequency. The loss is due to the polar nature of the material. Other influential factors are the material composition and external environments, particularly temperature.

The test data for the dissipation factor are usually obtained during the test for permittivity, as detailed in ASTM D150 (Ref. 5). The testing should include specimen identification parameters (Table 1-2), common test para-

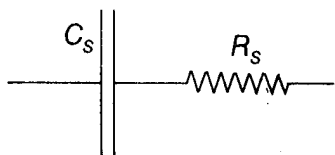


C_p = Capacitance
 R_p = Resistance

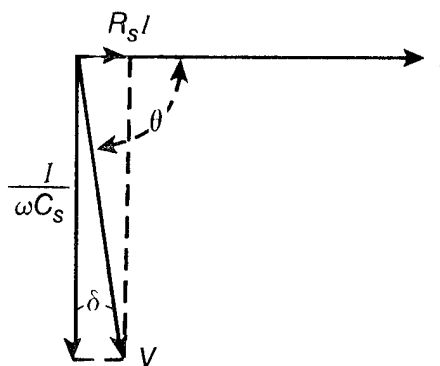


V = Voltage
 I = Current
 ω = Frequency
 θ = Phase Angle
 δ = Loss Angle

(A) Parallel Circuit



C_s = Capacitance
 R_s = Resistance



V = Voltage
 I = Current
 ω = Frequency
 θ = Phase Angle
 δ = Loss Angle

(B) Series Circuit

Figure 5-8. Dissipation Factor

meters (Table 2-4), and those parameters unique to the test, which are

1. *Dissipation Factor.* The average value of the tangent of the loss angle for each condition of test
2. *Frequency.* The applied frequency from 10^{-6} to 10^{12} Hz with the frequency increment at each decade
3. *Temperature.* The test temperatures should range, as suggested in Table 2-4, from -55° to 70° C (-67° to 158° F).
4. *Relative Humidity.* Basic testing should be performed at a relative humidity of 50%.
5. *Measurement Method.* The method of measurement is dictated by the appropriate frequency range of the test.
6. *Electrode.* The preferred electrode system is the guarded type, i.e., three-terminal, as specified in ASTM D150 (Ref. 5).
7. *Applied Voltage.* The voltage applied to the specimen for the test condition.

The range of dissipation factors for plastics can be from 0.0001 to 0.3; some materials will exceed the range of values. The low and high values reflect a low or high dielectric loss, respectively. Generally, it is important to minimize the amount of power dissipated into dielectric materials, and minimizing this power requires low dissipation factors.

The dissipation factor value varies as a function of frequency, as shown in Fig. 5-9. Although common practice is to report the dissipation factor at specific frequencies—60 Hz, 1 kHz, and 1 MHz—for engineering

use it is necessary that the full range be provided. Variation of the dissipation factor is due principally to the polarization effects within the material structure, as evidenced by the peak values. These values vary significantly with material.

Temperature also has a pronounced effect on the dissipation factor, as shown in Fig. 5-10. This effect is due to the smaller or greater molecular activity that accompanies higher temperatures, particularly with polar materials. Testing over a broad range of temperatures and frequencies can result in graphical presentation in the form of contour maps, as shown in Fig. 5-11.

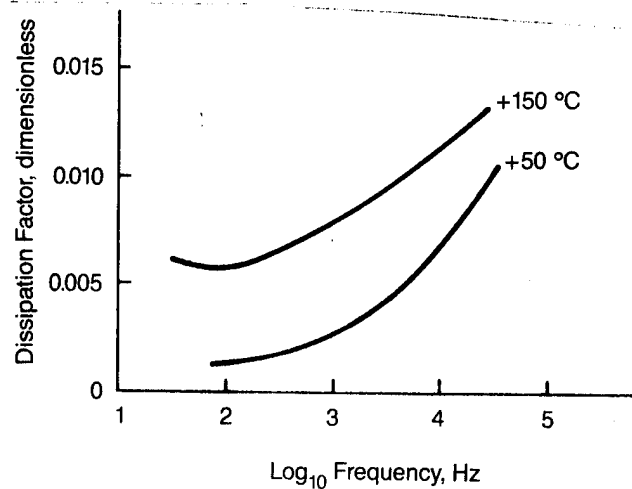


Figure 5-10. Dissipation Factor vs Frequency and Temperature

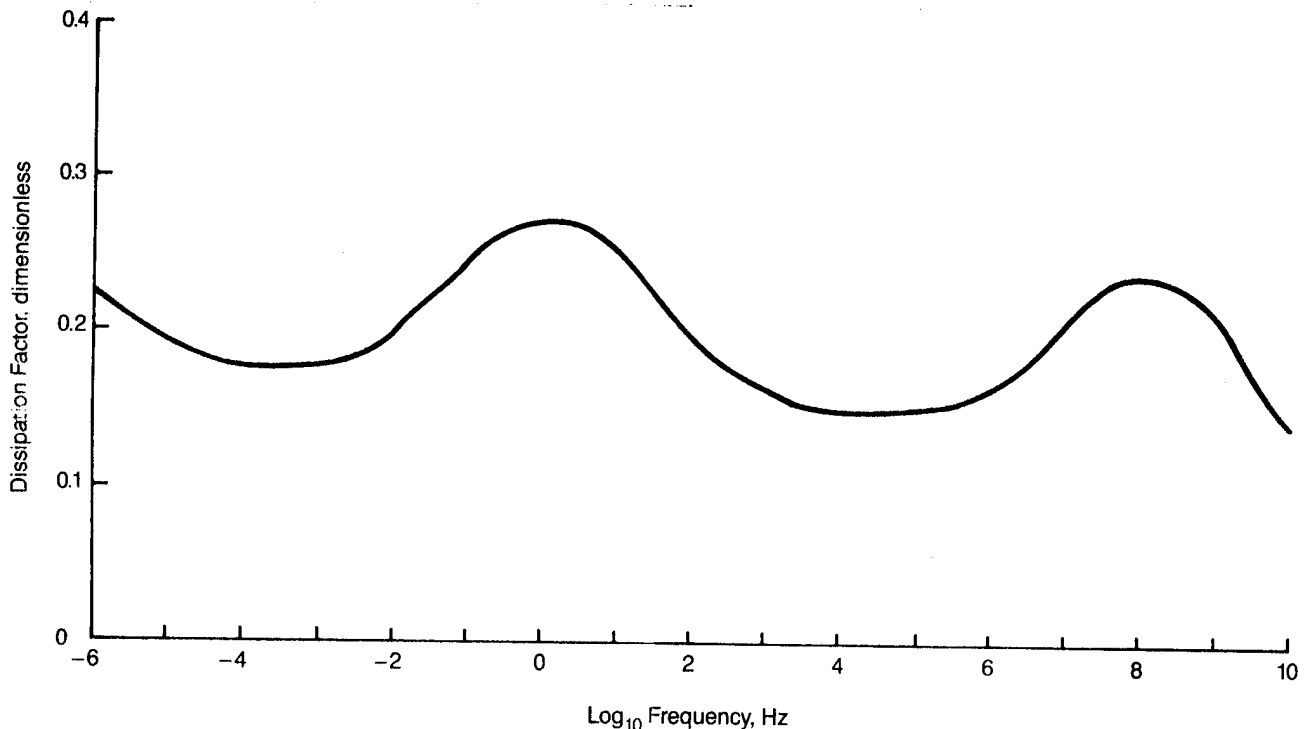
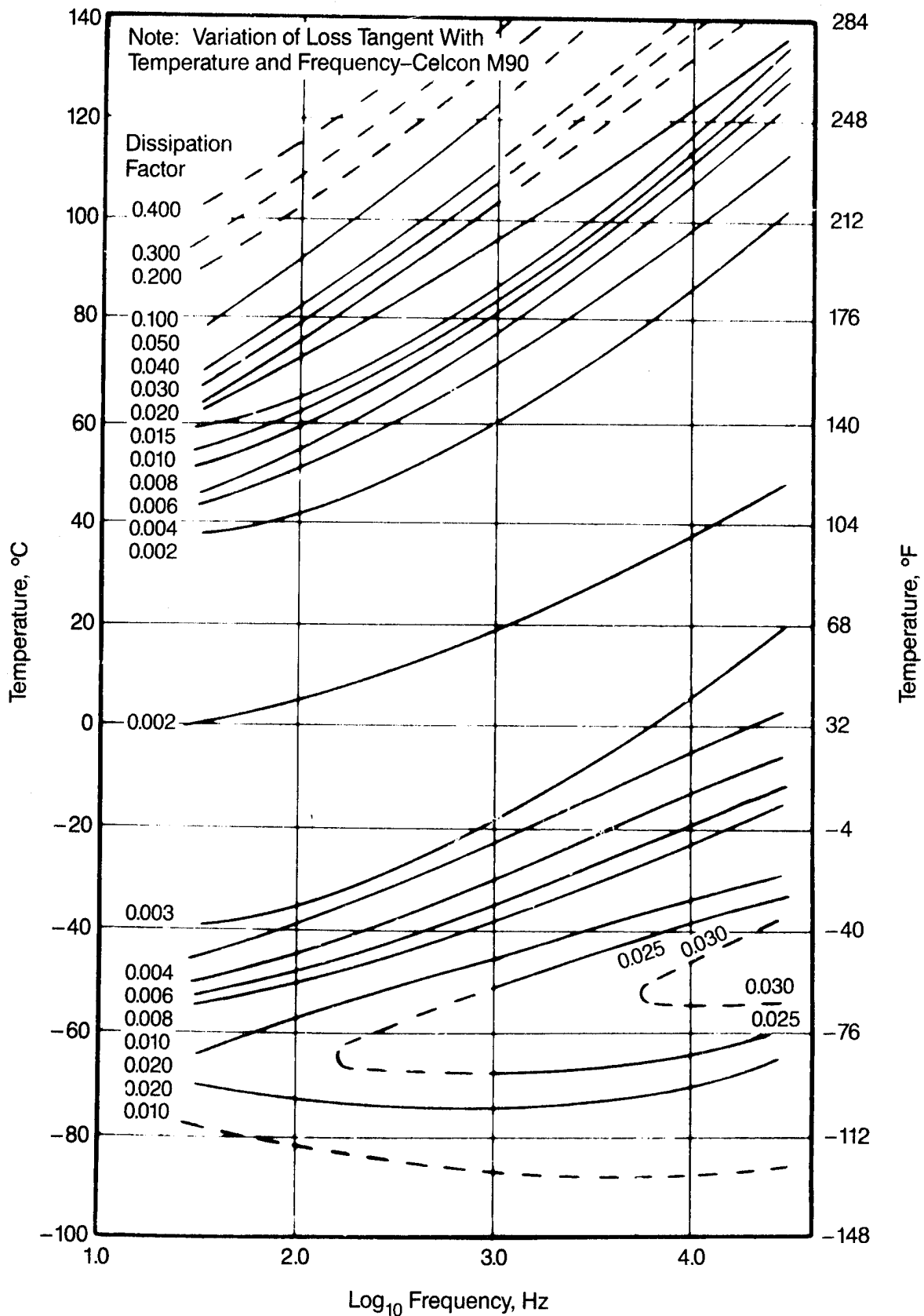


Figure 5-9. Dissipation Factor vs Frequency

MIL-HDBK-755(AR)



From *CELCON Design Manual*, Celanese Corporation, Celanese Engineering Resins, Summit, NJ.

Figure 5-11. Loss Tangent vs Frequency and Temperature

5-4.2 POWER FACTOR

Similar to the dissipation factor, the power factor (PF) is a measure of the relative dielectric loss for an insulating material. It is a dimensionless term that reflects the insulation quality, and it is defined as the ratio of the power dissipated in the form of heat to the energy required to charge the dielectric. The PF is expressed as the product of the sinusoidal voltage and amperes.

Numerically, it may be expressed as the cosine of the phase angle or the sine of the loss angle and, therefore, is mathematically related to the dissipation factor.

5-4.3 LOSS INDEX (LOSS FACTOR)

Similar to the dissipation and power factors, the loss index is a measure of the dielectric loss for an insulating material. Formally known as the loss factor, the loss index is a dimensionless term. It is defined as the product of the permittivity and the dissipation factor. For small loss angles for which the power factor is numerically equal to the dissipation factor, the loss index may be considered as the product of the permittivity and the power factor. This case, however, is special and the terminology should be discouraged.

5-5 ELECTRICAL RESISTANCE

Since insulating materials are used to isolate components of an electrical system from each other and from ground, it is desirable to have high resistance to the passage of current. The term "insulation resistance" has been used to describe electrical resistance and generally refers to the resistance between two electrodes. It is defined as the ratio of the direct voltage applied to the electrodes to the total current between them.

Insulation resistance is a vague term that actually embodies a combined effect of resistance to leakage of current through the body, i.e., the volume of the material, and along its surface (Refs. 8 through 13). The value of insulation resistance in ohms is a measure of an electrode system and does not suggest a relationship to the size or shape of the specimen. The volume resistance effect depends largely on the nature of the materials, whereas the surface resistance is mostly a function of surface finish and cleanliness. Insulation resistance is significantly affected by the many combined variables such as material composition, moisture content, temperature, relative humidity, surface cleanliness, and insulation design configuration.

To compare materials, common practice in the trade has been to express the volume and surface effects of a material in terms of volume resistivity and surface resistivity. Although use of insulating materials is quite extensive, the nominal environment for evaluation of resistivity is ambient air in which temperature and/or humidity vary. This implies that data collected when specimens are exposed to oil immersion, other gases,

simulated space environments, or other natural contaminants are considered special conditions of test. The resistivities are independently discussed in this paragraph along with the related terms of resistance and conductance.

Resistance in terms of preventing the burning of a conductive path across the surface of a material when a high voltage is applied between two electrodes has been termed arc resistance (Refs. 14 through 19).

5-5.1 VOLUME RESISTIVITY

In standard laboratory procedure (Ref. 8) volume resistivity is determined by applying a voltage across the specimen and measuring the resulting current in some convenient manner, as shown in Fig. 5-12. The result is a measure of the resistance between the two electrodes that cover opposite faces of the specimen. Volume resistivity is not a measure of resistance per unit volume, which is sometimes erroneously used; it is calculated from the volume resistance readings and the effective dimensions of the specimen. The units of volume resistivity are ohm·m (ohm·ft).

The test procedure for generation of volume resistivity data is detailed in ASTM D257 (Ref. 8). Testing should include specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test. These parameters are

1. *Volume Resistivity.* The average value of resistivity in ohm·m (ohm·ft) for each condition of test
2. *Specimen.* A disk 3.18 mm (0.125 in.) in thickness and 102 mm (4.02 in.) in diameter should be used as a standard.
3. *Temperature.* The test temperature should range, as suggested in Table 2-4, from -55° to 70°C (-67° to 158°F) or to higher temperatures, as appropriate for the material.
4. *Relative Humidity.* Testing should be performed at a relative humidity of 50%.
5. *Applied Voltage.* 100, 500, 1000, 2500, and 5000 V should be applied.
6. *Time of Electrification.* The length of time in minutes that voltage is applied to the specimen. Resistivities should be determined at intervals of 1, 10, 10^2 , and 10^3 min or when equilibrium is established.
7. *Electrode.* Circular, flat metal plates of the guarded type to conform to the specimen size

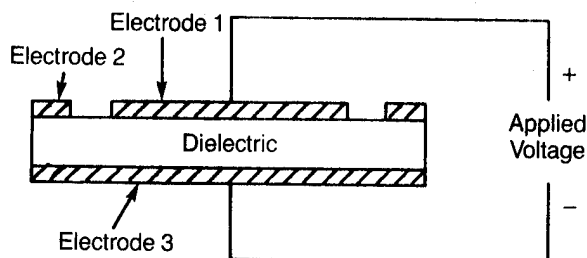


Figure 5-12. Volume Resistivity Schematic

8. *Method of Measurement.* The method used to determine resistivity.

Volume resistivity is a calculated value and has been used to differentiate between conductors and nonconductors. The nonconductors, or insulators, are materials that have resistivities of from approximately 10^6 to 10^{16} ohm·m (ohm·ft), whereas conductors range between 0 and 10 ohm·m (ohm·ft), and a class called semiconductors range between 10 and 10^6 ohm·m (ohm·ft). Most plastics fall within the nonconductor range, but a few exceed these limits. Since volume resistivity reflects resistance to current flow through a material, high values would be desired in applications for which greater resistance is needed.

The volume resistivity of a material is dependent on material composition and, naturally, the many environmental factors. If it is assumed that material homogeneity is maintained during manufacture, reproducing resistivity values should be easy. The main factors affecting performance are moisture and two factors—voltage stress and temperature—which alter the molecular structure. Although absorbed moisture will significantly affect resistivity, testing should be performed at low and high moisture contents only on a special basis for those materials considered to be moisture sensitive.

Although most data are reported at a standard electrification time of 1 min, it is well known that the volume resistivity varies with time and voltage stress. Testing at less than and beyond the 1-min period reveals that volume resistivity varies with the time of electrification, as shown in Fig. 5-13. The intent of extended times is to establish an

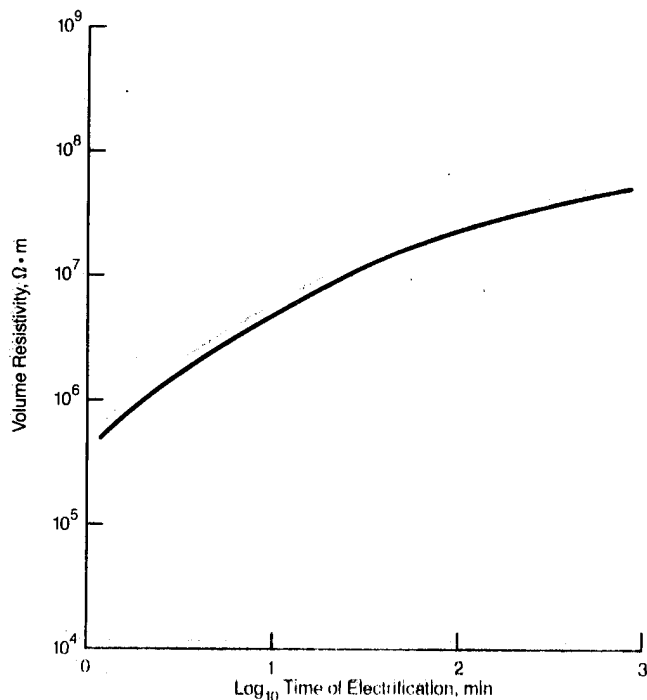


Figure 5-13. Volume Resistivity vs Time of Electrification

equilibrium condition. Coupling resistivity time measurement at the various temperatures can be combined to give an overall effect. Applied voltage has an effect on volume resistivity, as shown in Fig. 5-14, and requires consideration in the data presentation.

Volume resistivity values are relatively high at ambient temperature and are reduced significantly with increases in temperature, as shown in Fig. 5-15. This effect is due to the change in molecular activity of the plastic, especially at elevated temperatures.

5-5.2 SURFACE RESISTIVITY

To determine surface resistivity, as shown schematically in Fig. 5-16, the test configuration used to determine volume resistivity in ASTM D257 (Ref. 8) is normally employed. By alternating the position of the guard electrode, the resulting resistance is measured as the ratio of the direct voltage applied to the electrodes to that portion of the current between them, which is the result of a semiconducting medium in or at the surface. The material resistivity is the calculated value that represents the ratio of potential gradient to current per unit width of surface. The units of surface resistivity, unlike volume resistivity, are expressed in ohms and are independent of the unit of length.

The surface resistance measurement is only an approximation because volume resistance is nearly always involved in the measurement (Ref. 8). The measurement is largely a surface effect involving the material structure at

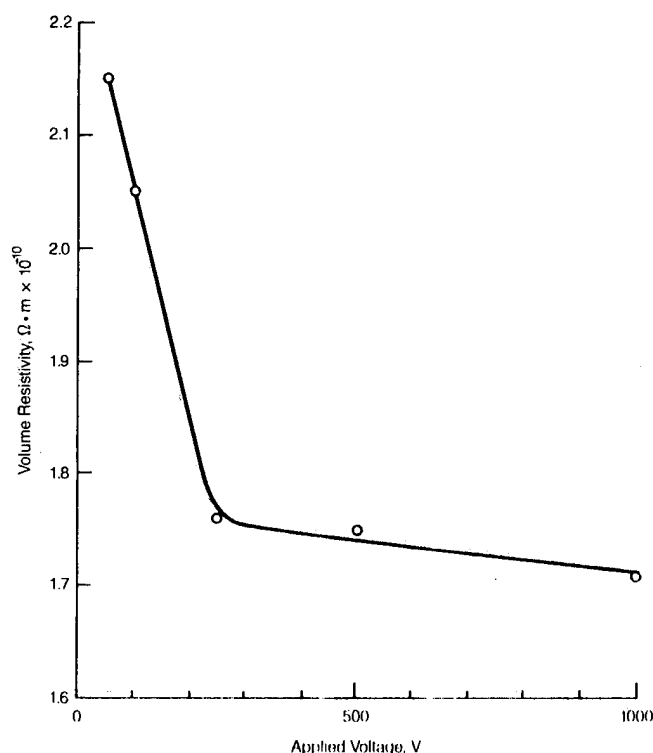


Figure 5-14. Volume Resistivity vs Applied Voltage

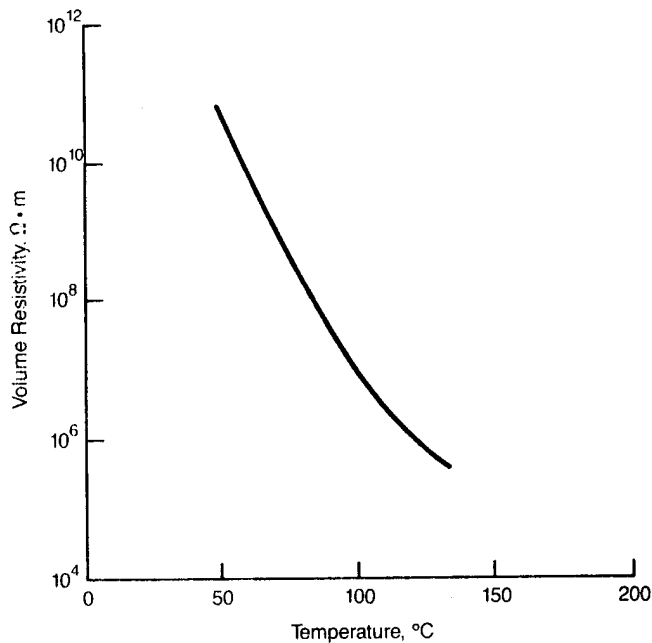


Figure 5-15. Volume Resistivity vs Temperature

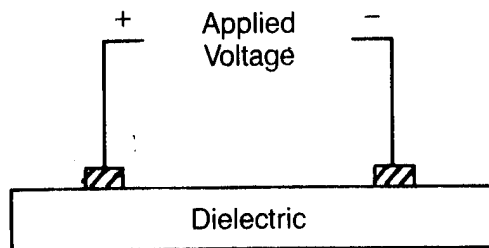


Figure 5-16. Surface Resistivity Schematic

the surface, the surface finish, moisture at the outermost layer of the material, moisture adjacent to the surface, and contaminants (dust, oil, etc.) on the surface. Surface resistivity is primarily a response at the surface of a material. It does not involve the bulk of material; therefore, it is not a material property in the usual sense. It is, however, a measure of how a material will collect and hold multiple molecular layers of water at its surface.

The test procedure for generation of surface resistivity data is detailed in ASTM Test Method D257 (Ref. 8). Testing should include specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test. These unique parameters are

1. *Surface Resistivity.* The average value of resistivity in ohms for each condition of test
2. *Specimen.* A disk 3.18 mm (0.125 in.) in thickness and 102 mm (4.02 in.) in diameter should be used as a standard.
3. *Electrode.* Circular, flat metal plates of the guarded type to conform to the specimen size

4. *Method of Measurement.* The method used to determine resistivity

5. *Applied Voltage.* The applied voltages should be 100 and 500 V.

6. *Time of Electrification.* The length of time in minutes that the voltage is applied to the specimen. Resistivities should be determined at intervals of 1, 10, 10^2 , and 10^3 min or when equilibrium is established.

7. *Temperature.* Testing should be limited to ambient and elevated temperatures, as suggested in Table 2-4.

8. *Relative Humidity.* Testing should be performed at relative humidities of 50% and 95%.

In summary, surface resistivity is not a material property in a true sense; it is a characteristic of the material surface as influenced principally by temperature and humidity. It is useful in support of design because it reflects a basic performance factor that cannot be neglected. In generated data the assumption must be made that the standardized test was conducted with clean laboratory specimens.

Surface resistivity is a calculated value and is used to ascertain the relative current leakage on the surface of a material. For the most part, data for surface resistivity are not readily reported in the trade literature. When subjected to a relative humidity of 50%, however, typical values of surface resistivities exceed 10^{18} ohms (Ref. 13). In the presence of 95% relative humidity, the values are significantly reduced by several decades and, in certain environments, to values of 10^5 ohms.

Generally, surface resistivity varies with temperature, but the influence of moisture may be such that the temperature effect is likely to be obscured. Testing at high relative humidity reflects the influence of moisture on performance, particularly for moisture-sensitive materials. Upon exposure to high humidity, i.e., 95%, at a fixed temperature, surface resistivity decreases with electrification time due to the absorptive effects at the surface of the material. For nonmoisture-sensitive materials this effect may be minimal.

5-5.3 ARC RESISTANCE

Arc resistance is a measure of an electrical breakdown condition along an insulating surface when subjected to high voltage. A schematic is shown in Fig. 5-17. The arcing, similar to corona, ionizes the air but then breaks down the surface of the material. The test has been used as a preliminary way to differentiate between thermosetting materials with regard to their tendency to form a conductive path on the surface. In general, thermoplastic material response is different and tends to resist the formation of conductive paths and to exhibit other forms of degradation. This difference in failure makes the comparison of material very difficult.

The arc resistance of a material is determined by measuring the total elapsed time in seconds of voltage

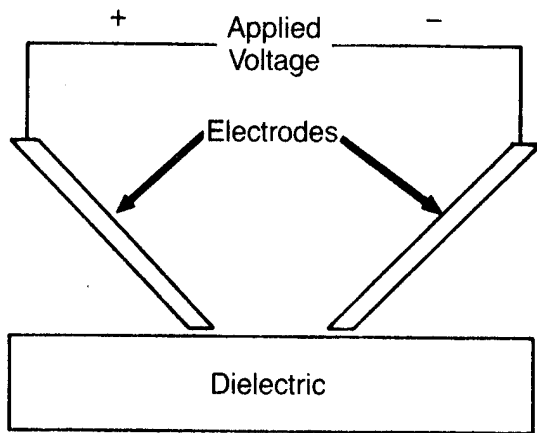


Figure 5-17. Arc Resistance Schematic

application until failure occurs. Failure may be in the form of a thin, wirelike line between electrodes (tracking), carbonization of the surface, cracking, ignition of the material, melting, or change in appearance. Thermosetting materials tend to carbonize, whereas thermoplastic materials do not and are more likely to soften and burn.

The arc resistance test performed in accordance with ASTM Test Method D495 (Ref. 14) simulates alternating current circuits having high voltage at very low currents (milliamperes). ASTM Test Method D495 (Ref. 14) has limited use because other high voltage and high current conditions may produce different results. Also the response is a surface phenomenon; therefore, the surface conditions significantly affect the results. More meaningful tests, as suggested in ASTM D495, are ASTM Test Methods D2132 (Ref. 15) and D2303 (Ref. 16).

Of the three service-oriented tests, the inclined plane test, ASTM D2303, may provide more meaningful results relative to the ranking of materials (Refs. 17 and 18). The dust and fog test, ASTM D2132, may be limited because it is better suited to assessing service life.

Testing for arc resistance should be performed in accordance with ASTMs D495 and D2303 to provide data for both dry and wet conditions. Testing should include specimen identification procedures (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test. These unique parameters are

1. *Arc Resistance Time*. The time in seconds required for breakdown along the surface of the specimen
2. *Temperature*. The test temperature should be limited to the nominal of 23°C (73°F).
3. *Voltage*. The applied voltage in volts
4. *Contaminant*. The contaminant should be ammonium chloride, as specified in ASTM D2303 (Ref. 16).
5. *Electrode*. The stainless strip and the tungsten rod electrodes should be used, as recommended in ASTM D495 (Ref. 14).
6. *Relative Humidity*. The relative humidity should be limited to the nominal of 50%.

Arc resistance is important for applications in which momentary flashover may occur. This possibility necessitates a material that resists the formation of a conductive path. The arc resistance test results, in accordance with ASTM D495 (Ref. 14), represent dry, ambient conditions of test and can be used as a preliminary measure of material suitability. Test data generated from ASTM D2303 (Ref. 16) provide arc resistance values with the use of a basic contaminant. High values of arc resistance indicate greater resistance to breakdown along the surface of the material.

5-6 CORONA RESISTANCE

The phenomenon termed "corona" is associated with high voltage applications that cause small, localized electrical discharges in the surrounding gaseous medium when the applied voltage exceeds the gas breakdown potential. The discharge is characterized by detectable luminosity caused by ionization of the medium (usually air) in the path of the high voltage discharge.

This electrical discharge, which may have a deleterious effect on the performance of plastic materials, is applied continuously for a finite period of time. Material degradation may be in the form of insulation erosion, cracking or embrittlement, change in physical dimensions, or change in surface conductivity.

Resistance to corona may be evaluated in accordance with ASTM D2275 (Ref. 19), a test method used to rate materials in terms of voltage endurance. During this test a voltage stress above the corona inception voltage is applied until material degradation occurs.

The effect of corona is a complicated phenomenon, is greatly influenced by the electrode and specimen geometry, and should eventually be evaluated in design configuration. Results are also affected by material impurities, induced stress, relative humidity, temperature, and electrical test parameters.

Testing for corona resistance should be performed in accordance with ASTM D2275. Testing should include specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test. These parameters are

1. *Specimen*. The nominal specimen thickness should be 3.18 mm (0.125 in.).
2. *Temperature*. The nominal temperature of 23°C (70°F) should be used.
3. *Relative Humidity*. The nominal relative humidity of 50% should be used.
4. *Surrounding Medium*. Testing should be performed in air, and the rate of air flow should be noted.
5. *Frequency*. Test results should be provided for a frequency of 60 Hz.
6. *Electrode*. The preferred upper electrode is 6.4 mm (0.25 in.) in diameter, and the larger electrode should be sized according to the test method.

7. *Voltage.* The levels of voltage applied to the specimen that result in corona; the lowest level is the corona inception angle.

8. *Time.* The time, in hours, at which failure occurs.

9. *Appearance.* A description of the test condition or mode that constitutes failure.

Corona resistance, as determined in accordance with ASTM D2275 (Ref. 19), is useful only as a preliminary evaluation or screening of materials for potential use. Data cannot be extrapolated to end use conditions unless the conditions of test and use are similar in geometry and environment.

The data generated in this test procedure have been limited to nominal conditions of temperature, relative humidity, specimen thickness, and frequency and will enable relative ranking of materials and a plot of the voltage versus time to failure for each material.

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CHAPTER 6

OPTICAL PROPERTIES

This chapter provides an overview of optical properties by focusing on light passage through transparent materials that are of interest for military applications. A discussion of optical properties is followed by a brief discussion of environmental factors that inhibit transparency.

6-0 LIST OF SYMBOLS

- c = speed of light in free space, m/s (ft/s)
- c_m = speed of light in material, m/s (ft/s)
- I_0 = intensity of incident light, lm/m² (ft-candle)
- I_R = intensity of reflected light, lm/m² (ft-candle)
- i = angle between direction of light beam in Material a and vector normal to surface, i.e., angle of incidence, deg.
- i_c = critical angle, deg
- n = refractive index of material, dimensionless
- n_a = refractive index of Material a, dimensionless
- n_b = refractive index of Material b, dimensionless
- r = angle between direction of light beam in Material b and vector normal to surface, i.e., angle of refraction, deg
- T = transmittance, %
- V = reciprocal dispersion of Abbe constant, dimensionless

6-1 INTRODUCTION

When the term "optical properties" is used, the association is with materials that are transparent or translucent. Generally, primary interest is in transparency, or the visual "see through" characteristics, and the ability of the material to transmit light. In optical applications translucency and opaqueness are of minimal interest, as are the reflective surface properties. Transparent materials require a final product form free of inclusions, stress gradients, or any other influence on the light reflective and refractive characteristics of the material. Imperfections may be introduced in the manufacture of the material itself or in the final product.

"Transparency" is a general term and refers to the optical homogeneity of the material. Although surface characteristics such as smoothness affect transparency, the bulk characteristics are of more interest. The quality of a transparent material is determined primarily by the amount of light scattered within it. Clarity, an associated term, is the degree to which a material permits details in an object to be resolved in the image.

The property known as refractive index is valuable in assessing both transparency and clarity. Variation in refractive index leads to scattering of light and/or aberration of the image. The refractive index and the resultant

light transmission characteristics are the principal properties needed for optical purposes.

The use of transparent materials in the military is also dependent on the field of application, and this dependency varies significantly in the undersea, land, and outerspace environments (Ref. 1). The choice of materials, such as glass or plastic, is very dependent on the overall characteristics of the material, not just on its optical properties. Thus the suitability of a material to a particular application is dependent on the system, which establishes the optical and durability requirements.

In this chapter the use of materials is discussed initially to introduce the considerations related to optical applications that should be addressed in development. This introduction is followed by discussion of pertinent optical properties. This chapter does not discuss optical design; it discusses only the properties useful in design.

6-1.1 APPLICATIONS

Plastic materials have gained significant use in optical applications not only for their transparency but for their many complementary features (Refs. 2 and 3). These include light weight, low cost, processibility, impact resistance, and freedom from design restrictions. One exception may be in the manufacture of very large plastic lenses, which tend to be costly. No adequate substitute, however, has been found for glass when chemical, ultraviolet light, and thermal resistance are considered (Refs. 4 and 5). Overall, the use of plastics for optical applications requires an understanding of these properties and the influence of the many other environmental factors.

Typical military uses of plastics in optical applications include aircraft windshields (Ref. 6), sighting devices, goggles, solar energy components, ballistic shields, and fiber optics. In most applications, transparency must be maintained throughout the service life of the equipment, and the effects of sun, wind, moisture, and dust—the elements that comprise the weathering environment—must be considered. Abrasion resistance is a material characteristic of high interest. Also most applications require structural (mechanical) integrity and resistance to the broad operating temperature requirements. Temperature is particularly important because the thermal expansion coefficient for optical plastics is relatively high. Failure by discoloration, distortion, or cracking is unacceptable.

able and therefore requires effective assessment in design.

Of the many transparent materials available, only a few have been identified for optical applications. These are polymethylmethacrylate (acrylic), polystyrene (styrene), polycarbonate, and a styrene/acrylic copolymer. Others that have generated some interest because of their special features are polymethylpentene and allyl diglycol carbonate. The remaining plastics are used over a wide range of areas, particularly packaging, novelties, displays, housewares, and other specialty applications.

The material properties of interest in design are concentrated on the ability of a material to transmit light and on the manner in which the light and images are transferred. The American Society for Testing and Materials (ASTM) test procedures list index of refraction, transmittance, and haze as basic optical properties.

6-1.2 ELECTROMAGNETIC SPECTRUM

The transparency characteristic of plastics for military use is not limited to visible light transmission aspects; it encompasses the full range of radiation emitted by the sun, i.e., wavelengths between 200 and 2700 nm. This radiant energy includes both the ultraviolet and infrared wavelengths. The discussion within this chapter, however, is limited to consideration of only the visible band.

The most fundamental parameter pertaining to optics is the electromagnetic spectrum. It defines the wavelengths of the various forms of energy, i.e., from cosmic rays to X rays to radio waves and beyond. A small band of the electromagnetic spectrum contains wavelengths sensitive to the human eye and is called the visible band, as shown in Fig. 6-1. It is bordered at the lower wavelength by ultraviolet light and at the higher end by infrared. The visible band ranges from 380 to 780 nm. The wavelength of approximately 550 nm is that wavelength at which the sensitivity of the human eye to visible light is at the maximum.

The visible band contains wavelengths that discriminate color from violet, blue, green, yellow, orange to red (Refs. 7 and 8). Within this band are many spectral lines.

The principal spectral lines are

1. Hydrogen red, 656.3 nm
2. Sodium yellow, 589.3 nm
3. Mercury green, 546.1 nm
4. Hydrogen blue, 486.1 nm.

Although other principal spectral lines have been defined, those listed are the most important.

6-2 REFRACTION

Refraction is the bending of light as it passes from one transparent medium to another. The bending is caused by a change in the velocity of the light as it passes from one medium to another.

6-2.1 REFRACTIVE INDEX

The speed of light traveling through a material is always less than that of light traveling through free space. The ratio of the speed of light through free space to the speed of light through a material is called the refractive index, or the index of refraction, of that material. Stated mathematically, this relationship is

$$n = \frac{c}{c_m}, \text{ dimensionless} \quad (6-1)$$

where

n = refractive index of material, dimensionless

$c = 3 \times 10^8 \text{ m/s } (9.8 \times 10^8 \text{ ft/s})$ = speed of light in free space

c_m = speed of light in material, m/s (ft/s).

The speed of a plane wave of light changes when passing from one material to another material with a different refractive index; therefore, the direction of the light will be modified, as shown in Fig. 6-2, if the incident light beam is not perpendicular to the interface. The relationship between the incident wave direction and the refracted, or exiting, wave direction is given by Snell's Law as

$$n_a \sin i = n_b \sin r, \text{ dimensionless} \quad (6-2)$$

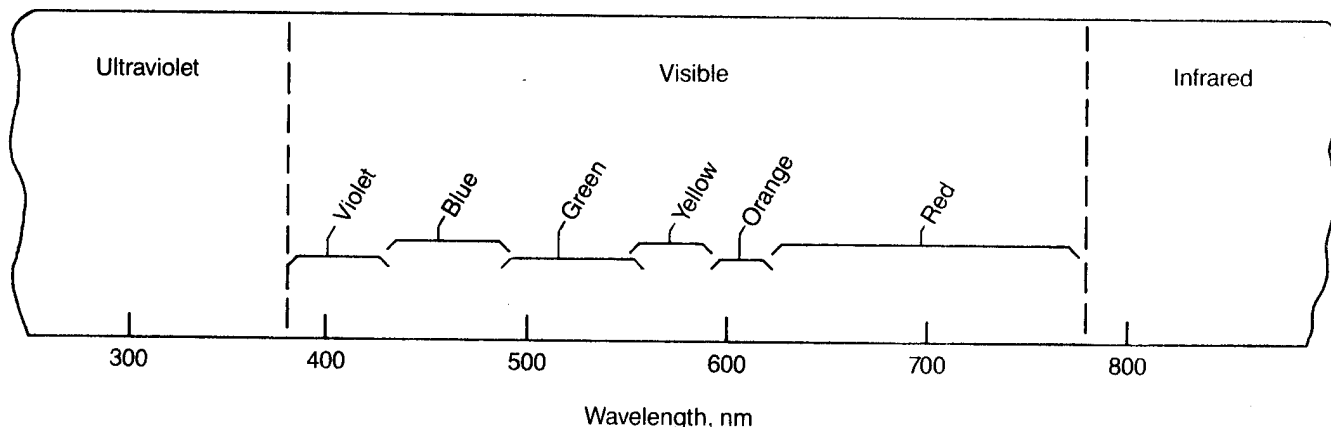


Figure 6-1. Visible Electromagnetic Spectrum

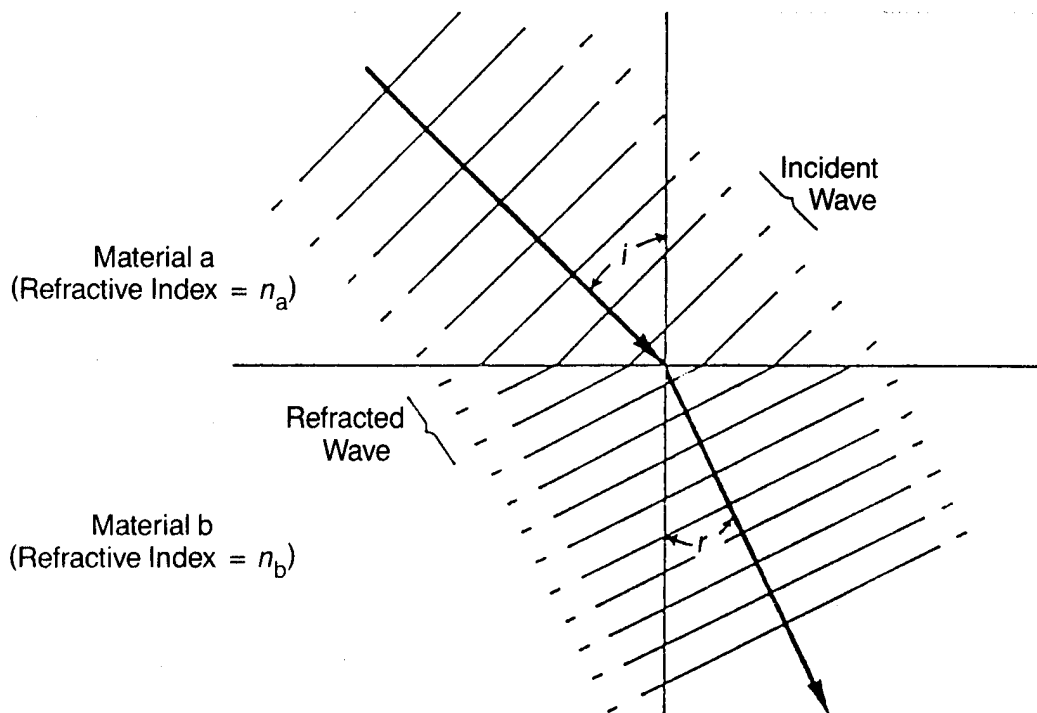


Figure 6-2. Refraction of Light

where

n_a = refractive index of Material a, dimensionless

n_b = refractive index of Material b, dimensionless

i = angle between direction of light beam in Material a and vector normal to surface, i.e., angle of incidence, deg

r = angle between direction of light beam in Material b and vector normal to surface, i.e., angle of refraction, deg.

When Material a is air, $n_a = 1$ and Eq. 6-2 becomes

$$n_b = \frac{\sin i}{\sin r}$$

When the medium is a vacuum, the refractive index is termed absolute. This assumes the measurement is made at a certain temperature and measured with a specific wavelength of light. Because the index of refraction for a vacuum is 1.000 and for air it is 1.000292, the measured indices are often used interchangeably, and the indices of refraction are quoted against air as a standard. The difference is significant, however, in certain engineering applications, namely, lenses used in vacuum or in near-vacuum environments.

The index of refraction for any material is dependent on the wavelength of light for which the measurement is made. Several spectral lines and their respective wavelengths are listed in Table 6-1.

TABLE 6-1. SPECTRAL WAVELENGTHS

WAVELENGTH (nm)	SOURCE	REFRACTIVE INDEX SUBSCRIPT	COLOR
780.0	Rubidium (Rb)		Red
768.0	Potassium (K)	A'	Red
656.3	Hydrogen (H)	C	Red
643.8	Cadmium (Cd)	C'	Red
589.3	Sodium (Na)	D	Yellow
587.6	Helium (He)	d	Yellow
546.1	Mercury (Hg)	e	Green
486.1	Hydrogen (H)	F	Blue
480.0	Cadmium (Cd)	F'	Blue
435.8	Mercury (Hg)	g	Blue
404.7	Mercury (Hg)	h	Violet

Within this group, the sodium (Na) light source, or the yellow D line at 589.3 nm, is the most commonly listed single-source measurement. Its designation would be n_D . Of the remaining light sources, the blue end n_F (486.1 nm) and red end n_C (656.3 nm) are typically reported for use in determining light dispersion.

The index of refraction can be determined by various methods, but the standard is ASTM D542 (Ref. 9) which uses an Abbe refractometer. The indices are determined by using a monochromatic light source such as a sodium or mercury lamp. The refractive index is primarily influenced by wavelength and temperature; therefore, testing should be conducted for a number of spectral lines and temperatures. ASTM E308 (Ref. 10) provides a listing of light sources for the wavelengths within the visible spectrum (380 to 780 nm).

Testing for the refractive index should include the specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters that are unique or modified. The unique parameters are

1. **Refractive Index.** The average value of refractive index for the number of specimens measured
2. **Temperature.** The test temperatures desired are -25° , 0° , 23° , and 50°C (-13° , 32° , 73° , and 122°F).
3. **Wavelength.** Specimens should be evaluated throughout the visible spectrum (380 to 780 nm) at each of the temperature conditions. Measurements should be

made for at least six wavelengths from 405 to 768 nm and should include measurements at 405, 486, 589, and 657 nm.

Tabulated data for refractive index can be plotted as illustrated in Figs. 6-3 and 6-4. The variation of refractive index as a function of wavelength at 23°C (73°F), as shown in Fig. 6-3, is typical of most plastics; the variation of refractive index with temperature at constant wavelength is generally linear, as illustrated in Fig. 6-4.

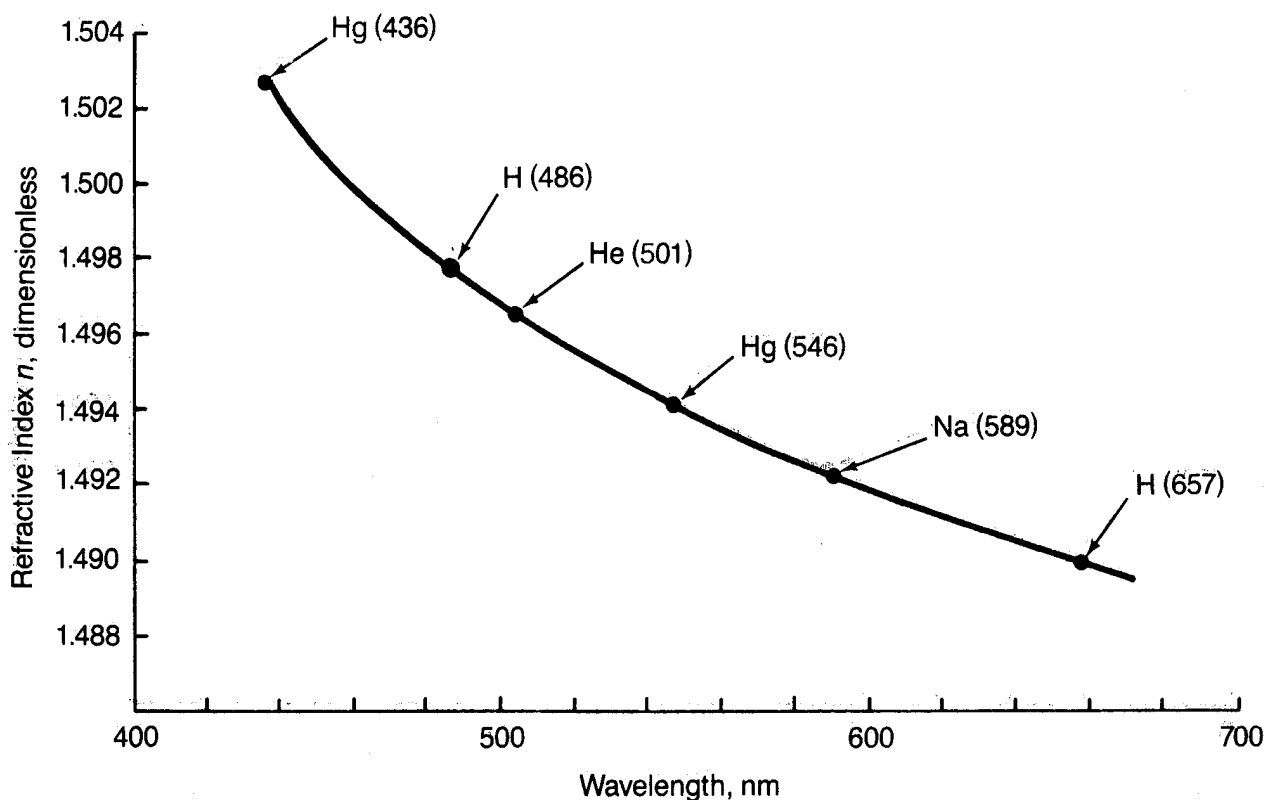
The refractive indices of various plastics range from approximately 1.47 to 1.59. Some plastics that are transparent in thin films do have indices below 1.40, and other experimental materials have measured indices above 1.60. The refractive indices are useful in engineering applications dealing with light dispersion and in fiber optics.

6-2.2 DISPERSION

Dispersion is a measure of chromatic aberration, or the degree to which white light will separate into its constituent colors. By convention, it is the numeric difference between the index of refraction for the F (486.1 nm) and C (656.3 nm) light sources.

$$\text{Dispersion} = n_F - n_C, \text{ dimensionless.} \quad (6-3)$$

The phenomenon has also been conventionally ex-



From "Acrylic Polymers for Optical Applications" by Robert W. Jans, published in SPIE Volume 204, *Physical Properties of Optical Materials*. Published by the Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, August 1979.

Figure 6-3. Refractive Index vs Wavelength (Ref. 11)

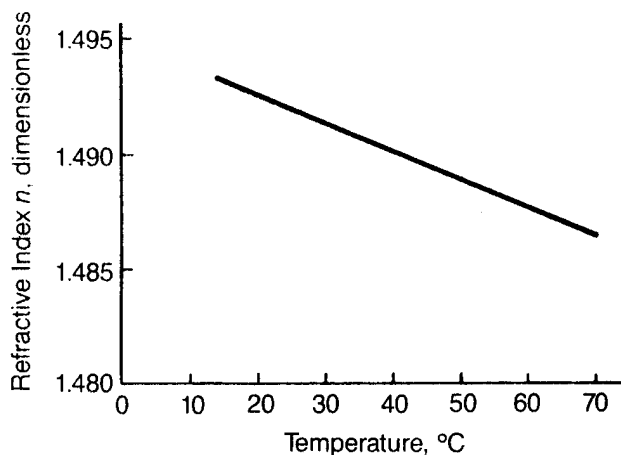


Figure 6-4. Refractive Index vs Temperature

pressed as the reciprocal dispersion or Abbe constant V given the expression (Ref. 12)

$$V = \frac{n_D - 1}{n_F - n_C}, \text{ dimensionless} \quad (6-4)$$

where the refractive index for the sodium Source D (589.3 nm) is used. The smaller the value of V , the greater the separation of colors.

These dispersion parameters are calculable functions that indicate the dependence of the indices of refraction, which are dependent on wavelength and temperature. Use of standardized data is important because dispersion terms are used in the design of lenses.

6-2.3 CRITICAL ANGLE

When a light ray passes from a more dense to a less dense medium, the refracted angle is always greater than the incident angle. When the angle of incidence i at the interface—usually a transparent material and air—is increased so that all the light is refracted along the interface (path AOB, Fig. 6-5), it is called the critical angle i_c .

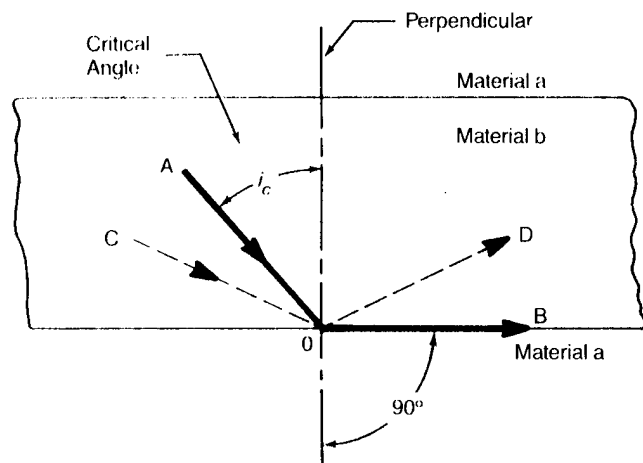


Figure 6-5. Critical Angle

This occurs when the angle of refraction r is 90 deg.

When the critical angle is exceeded, the light is totally reflected back (path C0D, Fig. 6-5) into the denser medium. This reflection occurs with any transparent material having an index of refraction greater than unity. The phenomenon of total internal reflection is useful in plastics applications because it is the basis for transmission of light through transparent rods and fibers known as "light piping".

The critical angle i_c is calculated from the relationship

$$i_c \sin^{-1} = \frac{n_a}{n_b}, \text{ deg} \quad (6-5)$$

where

n_b = refractive index of denser material, dimensionless

n_a = refractive index of less dense material, dimensionless

When air is the less dense material, i.e., $n_a = 1$, the critical angle is

$$i_c = \sin^{-1} \frac{1}{n_b}, \text{ deg.}$$

The index of refraction varies with wavelength and temperature; thus the critical angle will vary with the light source and the temperature.

6-3 LIGHT TRANSMISSION

The light transmission characteristics of a plastic reflect its ability to transmit wavelengths of light. The two characteristics, or properties, that principally indicate the degree of visible light transmission are transmittance and haze. Transmittance is a measure of the radiant flux transmitted, whereas haze is the amount of radiant flux lost due to light scattering.

The reflective surface and absorptive effects are related to transmittance. Reflection of the incident beam accounts for a large loss of incident radiant flux, whereas the losses due to absorption are generally small. Other factors affecting light transmission are specimen homogeneity, geometry, and quality of manufacture.

Although light transmission and haze are of most interest in optical design, reflectivity is directly associated with light transmission and does warrant consideration. Accordingly, the relationship between reflectivity and transmittance is discussed in the paragraphs that follow.

6-3.1 REFLECTANCE

Reflectance is generally described as a ratio of the reflected luminous flux to the incident flux. The mathematical relationship that describes this phenomenon is

known as Fresnel's equation (Ref. 12):

$$I_R = \frac{1}{2} \left[\frac{\sin^2(i - r)}{\sin^2(i + r)} + \frac{\tan^2(i - r)}{\tan^2(i + r)} \right] I_0, \quad (6-6)$$

lm/m²(ft-candle)

where

I_0 = intensity of incident light, lm/m²(ft-candle)

I_R = intensity of reflected light, lm/m²(ft-candle)

i = angle of incidence, deg

r = angle of refraction, deg.

For transparent materials the reflected light is directly related to the angle of incidence and angle of refraction and to geometric factors and surface finish. As discussed in par. 6-2.1, the angle of refraction is related to the refractive index, as shown in Eq. 6-2.

The amount of light reflected is highly dependent on the angle of incidence. As shown in Fig. 6-6, the percent of reflected light is very low when the incident beam is parallel to the surface and increases exponentially at large angles. For an angle of incidence of zero and a transparent acrylic material in air with a refractive index of 1.5, the percentage of reflected light at the surface is approximately 4% (Refs. 11 and 12). As the angle of incidence is increased, the percentage of reflected light increases gradually until the angle exceeds 40 deg, from which the exponential increase reaches 100% as the angle of incidence approaches 90 deg.

If at the zero angle of incidence the reflected light is 4%, the light reflected internally would be approximately 4%. The amount of internally reflected light becomes important when the light transmission characteristics are considered.

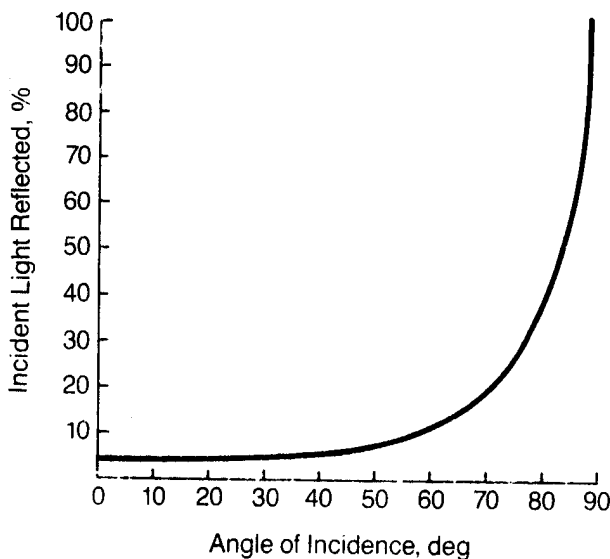


Figure 6-6. Reflection of Light ($n = 1.5$ at 23° C (73° F))

The reflective losses for acrylic-type plastics are the lowest of the optical plastics because the index of refraction of acrylics is the lowest for the plastic materials. The other plastic materials have slightly higher values of refractive index and thus higher losses.

Test methods (Ref. 8) have been developed to measure the reflecting property of a shiny, or lustrous, surface with respect to glass. This property, however, is generally associated with mirrorlike surfaces and does not warrant testing on a broad scale. Because most military applications demand nonreflective surfaces, molded products, unless otherwise specified, are made with shiny surfaces that duplicate the polished mold surface.

6-3.2 TRANSMITTANCE

Transmittance is the fraction of incident light that passes through a material. Theoretically, the amount of light that can be transmitted is always less than 100% because there are losses in the form of reflected and scattered light. The maximum transmittance is calculable and is derived from Fresnel's equation, which is described in par. 6-3.1.

Maximum transmittance occurs when the band of light is perpendicular to the surface. This perpendicularity minimizes reflection at the incident surface. Transmittance is a function of the angle of incidence and will vary from a maximum at 0 deg to a minimum at 90 deg, as shown in Fig. 6-7. As illustrated in Fig. 6-7, the transmittance represents that portion of the light transmitted at the first, or incident, surface. At 0 deg the transmittance is approximately 96%. This value indicates a reflective loss at the first surface of approximately 4%.

When the angle of incidence is 0 deg, Fresnel's equation can be modified in terms of total transmittance T (Ref. 12) as

$$T = \left[1 - \frac{(n - 1)^2}{n^2 + 1} \right] 100, \% \quad (6-7)$$

When a refractive index value of 1.5 is used — an average value for acrylic plastics — the transmittance percentage is approximately 92%. This implies that approximately 8% is reflected back on the incident beam (Ref. 12). As noted in par. 6-3.1, approximately 4% is lost at the incident reflecting surface; therefore, the remaining 4% is lost internally. Of this 4% most is lost by reflection at an inner surface and a small portion through light scattering.

The transmittance values provided in Fig. 6-7 are based on Fresnel's equation and represent the maximum value that can be obtained for an acrylic material. Plastics of higher refractive indices have higher losses and thus lower inherent transmittance values. From an end use, i.e., practical, point of view, transmittance varies with the wavelength of the light source, specimen thickness (Ref.

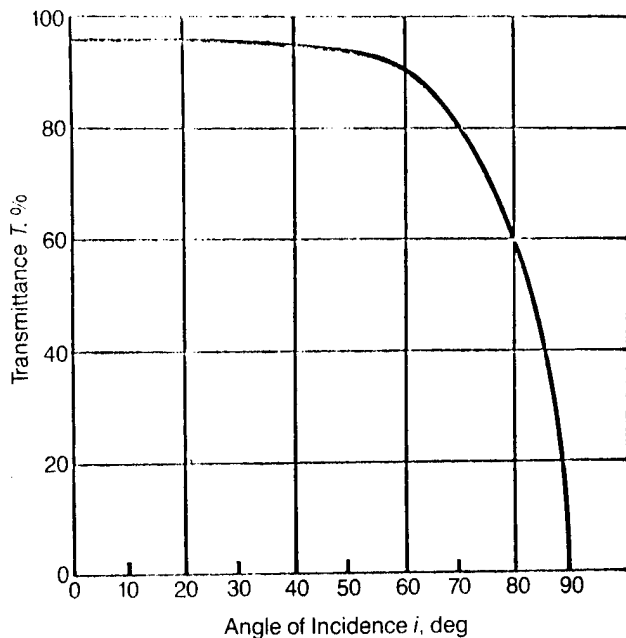


Figure 6-7. Transmittance vs Angle of Incidence

7), and material additives. These variations necessitate that testing be performed to determine transmittance values for each material of interest.

Testing of plastics for light transmission normally is performed in accordance with ASTM D1003 (Ref. 13). Another test procedure used is ASTM D1746 (Ref. 14), which was developed for plastic sheeting. It, however, is limited to determination of transmittance between a wavelength of 540 to 560 nm, i.e., the wavelength range in which the greatest visual acuity, or human eye sensitivity, occurs. ASTM D1746 (Ref. 14) is therefore not appropriate for use. ASTM D1003 (Ref. 13) is the preferred method for testing transparent plastics. The procedures in ASTM D1003 are consistent with ASTM E308 (Ref. 10), which addresses the spectral characteristics, or that computed quantity that is a function of wavelength. ASTM E308 (Ref. 10) is based upon spectrophotometry for the visible spectrum (380 to 780 nm) and recommends use of International Commission of Illumination (CIE) Source C unless another light source is justified. For purposes of general materials characterization, the recommended Source C is preferred.

Testing for light transmission should include the appropriate specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters that are unique or modified. These unique parameters are

1. **Transmittance.** The diffuse transmittance, or diffuse luminous transmittance, is the ratio of transmitted-to-incident light reported in percent. The incident light is conventionally measured in terms of total transmittance.

2. **Wavelength.** The wavelength of the visible band

for the transmittance determination. Measurements should be made for at least six wavelengths from 405 to 768 nm and should include measurements at 486, 589, and 657 nm.

3. **Procedure.** The procedure should be B, which specifies use of a recording spectrophotometer. This procedure should include use of CIE Source C as appropriate at the test wavelengths.

4. **Thickness.** The nominal specimen thickness should be 3.18 mm (0.125 in.).

5. **Temperature.** All tests should be conducted at 23°C (73°F).

Generally, transmittance values are provided in percentages and are termed diffuse transmittance, or luminous transmittance. Regardless of the adjective used, the values reflect the degree to which light passes through a material and, in essence, the degree of transparency. The higher the transmittance, the better the transparency.

When transmittance measurements are made at specific wavelengths—in essence, monochromatic radiation—the results generally are termed spectral transmittance. It is comparable to luminous transmittance and measures the energy transmitted at each wavelength.

A typical plot of transmittance versus wavelength for an acrylic material is shown in Fig. 6-8. It indicates that transmittance in the visible spectrum is constant, and therefore it indicates the transmission of all wavelengths to the same extent. Testing for transmittance in the visible region is essentially unaffected by thickness (Ref. 11). Outside the visible ranges, however, particularly at ultra-

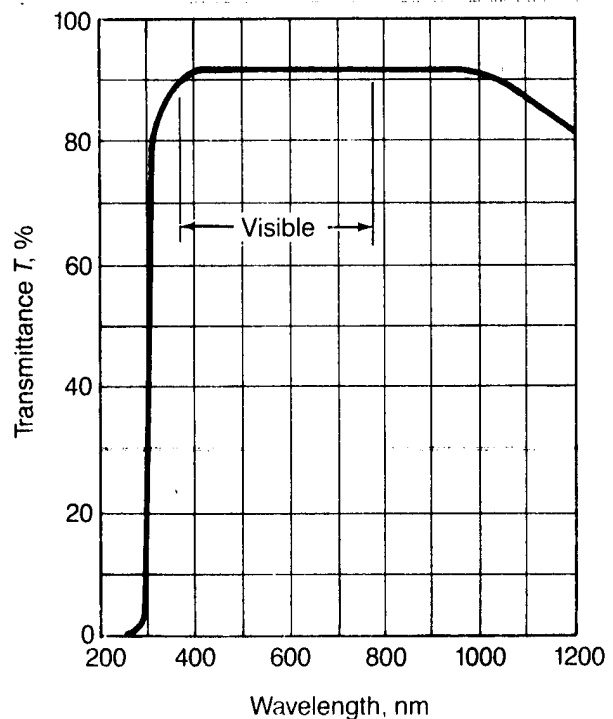


Figure 6-8. Transmittance vs Wavelength (Ref. 6)

violet wavelength, thickness does have an effect on transmittance.

As described in this paragraph, testing has been restricted to the visible spectrum. Interest in wavelengths outside this range does exist and eventually should be included in an engineering property base.

Another variable not considered in this chapter is the influence of color (Refs. 12 and 15) on the transmittance of transparent plastics. This is a specialized area and should be considered for testing on a special use basis.

6-3.3 HAZE

Haze is defined as the percentage of transmitted light that deviates from the incident beam. In general, it is light scattered forward at high angles, and it does not include light scattered at very low angles, i.e., less than 0.5 deg. This fact may lead to some lack of correlation between laboratory measurements and visual effects (Ref. 12). The haze measurement, however, does indicate the degree of loss in contrast to be expected: The higher the haze value, the greater the loss in contrast. Materials with haze values greater than 30% are considered translucent (Ref. 13). (Incidentally, this percentage defines the distinction between translucent and transparent materials.)

The haze measurement is also an indication of the clarity of a material, i.e., the capacity to permit details of an object to be observed through it. Clarity is perfect when no light is scattered. Clarity is indicated by the degree of transmittance because transmittance and haze are so closely associated. Although clarity would be measured fundamentally by determining the change in angular separation of points on the object resolved through a specimen, haze is a suitable indicator.

Testing for haze is performed in accordance with ASTM D1003 (Ref. 13), the same test method used for transmittance. Testing for haze, however, does not demand the extent of testing required for transmittance, but because haze is calculated from the parameters used to calculate transmittance, the data should also be provided. Therefore, haze should be reported in a similar manner, i.e., as a function of wavelength and thickness.

The haze values reported for plastics are in percent and reflect the degree of light that is not transmitted because of scattering. Typical values will vary from 1 to 5% for materials used in applications requiring transparency. When plotted as a function of thickness and wavelength, haze values will indicate the relative ability of a material to transmit an image clearly. These values do not substitute for actual experimentation in the design configuration; they are to be more of a screening mechanism during the selection of materials.

6-4 ENVIRONMENTAL FACTORS

The optical properties of plastics degrade through discoloration, distortion or loss of surface quality. These are

due to natural and induced environments. Natural factors -- such as sunshine, rain, wind, and dust -- may severely degrade the surface properties of a material, but also influential are the induced factors that result from the handling and maintenance of optical devices. Other environmental effects such as heat, aging, and chemical attack also lead to optical degradation. In all, testing should be performed to assess material response in the end use configuration.

To aid the designer, ASTM test methods ASTM D1044 (Ref. 16) and ASTM D1925 (Ref. 17) are available to assess a material for use in an abrasive environment and for change in material color with age, respectively. These two methods are end use oriented and provide basic data for use in material selection and each is described in detail in the paragraphs that follow.

6-4.1 SURFACE ABRASION

The abrasion of transparent material surfaces can result from many causes. Transparent plastics used in goggles (Ref. 18), aircraft windshields, and other see-through devices are more susceptible to surface defects than their glass counterparts. Plastics are softer and more easily abraded or scratched in normal use. One way to characterize resistance to abrasion is to measure optical effects in the laboratory for abraded specimens.

ASTM D1044 (Ref. 16) is the procedure used to measure the percentage of transmitted light that is scattered due to the abraded surface. The test procedure provides a standard means of abrading the surface by using a Taber abraser. The measurement of scattered light or haze for abraded specimens is performed in accordance with ASTM D1003 (Ref. 14), as described in par. 6-3.3. The data are suitable for comparing materials subjected to this type of abrasion.

Testing for surface abrasion should include the specimen identification parameters (Table 1-2), the test parameters (Table 2-4), and those parameters that are unique or modified. These unique parameters are

1. *Haze*. The average value of the scattered light in percent when tested in accordance with light Source C in ASTM D1003

2. *Abrader Wheel*. A calibrated wheel designated CS-10F should be used.

3. *Abrader Load*. An abrader load of 500 g should be used as a standard.

4. *Number of Cycles*. The number of cycles should be 0, 10, 25, 50, 100, and 500.

5. *Temperature*. All tests should be conducted at 23°C (73°F).

The results of the ASTM D1003 test provide a relative measure of transparent material resistance to surface abrasion. The test procedure is meant to be unique to windows or enclosures requiring continued transparency. Other surface abrasion tests are available to assess severe

surface abrasion and mar resistance; both of which are covered in Chapter 7.

The test for haze done in accordance with ASTM D1003 provides the degree of light scattered due to the surface aberrations. Testing for haze at various cycles of abrasion permits a plot that indicates the increase of haze with an increase in the number of cycles. When compared to plots of other materials, this plot indicates the level of resistance (percent haze) and the severity with time (cycles).

6-4.2 YELLOWNESS INDEX

Some clear plastics tend to be yellowish or to become yellow with time, particularly in thicker sections. This yellow hue may be somewhat inherent or may be the result of unavoidable impurities formed during the manufacturing process (Ref. 19). More important, however, is the yellowing that can develop due to extended periods of exposure to sunlight. Yellowness is significant because it reduces light transmission.

ASTM D1925 (Ref. 17) describes a test for this change in color and provides data in terms of a yellowness index (YI), which is the magnitude of yellowness relative to magnesium oxide for CIE Source C. The index provides data on basic, inherent yellowness and enables assessment of degradation due to exposure to heat, light, or other environmental elements, particularly sunlight. This test procedure is performed with a spectrophotometer, as recommended in ASTM D308 (Ref. 10).

Testing for this change in color should be performed in accordance with ASTM D1925. The test report for YI should include the appropriate specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters that are unique or modified. These unique parameters are

1. *Yellowness Index.* The magnitude and direction (sign) are the YI of the material prior to and after environmental exposure.

2. *Specimen Thickness.* The nominal specimen thickness should be 3.18 mm (0.125 in.). Testing should also be performed at 6.40 and 12.7 mm (0.252 and 0.5 in.).

3. *Environment.* The principal environment for exposure should be an artificial light source, and measurements of change should be made at monthly increments up to one year.

The artificial light source mentioned in No. 3 should duplicate the spectral energy distribution of sunlight. An apparatus useful for this purpose is described in Chapter 8 and is detailed in ASTM D2565.

The YI provides a numeric value that compares the yellow color against magnesium oxide as a standard. Along with the index value, a plus (+) or minus (-) sign is provided; the plus sign indicates the presence of yellowness, and the minus sign, a bluish color. More important for use, however, is the change in the YI subsequent to

environmental exposure. This change, expressed in percent, will reflect the anticipated change in the material over time.

The index change due to exposure to an artificial light source is the result of direct, continuous exposure, principally ultraviolet degradation. The index reflects a change in color but is not directly correlated with actual exposure conditions due to other combined conditions or tests such as temperature, variation, and surface degradation effects.

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CHAPTER 7

PHYSICAL AND SURFACE PROPERTIES

This chapter contains a number of material characteristics that have been arbitrarily combined into two groups, physical properties and surface properties. Each characteristic is discussed and its impact on engineering applications is emphasized.

7-0 LIST OF SYMBOLS

- F_f = force of sliding friction, N (lb)
- F_n = normal force pressing surfaces together, N (lb)
- P = contact pressure, Pa (psi)
- V = surface velocity, m/s (ft/s)
- μ = coefficient of friction, dimensionless

7-1 INTRODUCTION

This chapter discusses two groups of properties; those categorized as physical properties and those dealing with surface characteristics. Physical properties are those inherent in the bulk of the material and not categorized in any other group, e.g., mechanical, thermal, or optical. The surface properties included pertain to surface characteristics and relate to the relative motion between materials.

7-2 PHYSICAL PROPERTIES

The two physical properties discussed are the basic material characteristics of density and hardness. Generally, these properties are routinely characterized, yet they serve an important function during the early screening of materials.

7-2.1 DENSITY (SPECIFIC GRAVITY)

Density and specific gravity are two terms used to describe the inherent physical property of mass per unit volume. Although the terms are used interchangeably, there is a slight difference in their meanings. Density is expressed in grams per cubic centimeter (pounds per cubic inch), whereas specific gravity is dimensionless and is the ratio of the mass of a unit volume of material in air to the mass in air of an equal volume of distilled water at the same temperature, usually 23°C (73°F). The dissimilarity is in the fact that the density of water is slightly less than 1 at 23°C (73°F) (in fact it is 0.9975 g/cm³ (0.0360 lbm/in.³)). For practical purposes the density of water is considered to be unity.

Two American Society for Testing and Materials (ASTM) test methods are used to determine density. ASTM D792 (Ref. 1) is used to measure specific gravity and to calculate density. Specific gravity is calculated by displacement of liquid and determination of the change in

weight. ASTM D1505 (Ref. 2) determines density directly by use of a liquid density gradient column. This method quickly assesses density of small samples.

For reporting values, density may be determined in accordance with ASTM D792 (Ref. 1) or ASTM D1505 (Ref. 2). Test data should include specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters that follow:

1. *Density.* The average mass per unit volume in units of grams per cubic centimeter (pounds per cubic inch)

2. *Test Procedure.* For testing in accordance with ASTM D792 (Ref. 1), the procedure used is A1, A2, A3, or B.

3. *Temperature.* The test temperature should be limited to 23°C (73°F).

For design purposes, density is the parameter of interest. Density is primarily used for volume-versus-weight relationships and for part cost determination. Density is also useful in material comparisons such as strength-to-weight and cost-to-weight ratios.

7-2.2 HARDNESS

In metals technology material hardness is generally associated with mechanical properties because the hardness measurement correlates with strength. In this handbook hardness is classified as a physical property because its use in predicting plastic response to a mechanical force is not accepted in the plastics field. In this chapter hardness is viewed as a property dependent on the inherent physical structure of the material and is used only for relative comparison of materials.

Hardness tests for plastics are derived from metals, i.e., hardness is expressed as a measure of the resistance of the material to indentation and there is a direct relationship with material strength (Ref. 3). Many test methods have been devised to measure hardness of metals, either by indentation resistance to a rigid body or by the ability of a material to scratch any material of a lower hardness (Mohs' Test).

Because of the nature of polymeric materials, hardness tests performed are of the indentation type and have been adapted from metals technology. The hardness value is a number that indicates either the relative depth to which a metal ball or indenter will penetrate or the rebound

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efficiency upon load removal. Generally, the higher the number, the harder the material. Although an analytical approach has been developed to estimate the material modulus determined from indentation tests (Ref. 4), this use is not considered practical for development applications. The hardness test is time dependent, i.e., influenced by material creep and creep recovery characteristics, and this influence limits its usefulness for property determination. Also hardness is not suitable for use as an index of abrasion, scratch, or wear resistance as it is in metals technology.

Generally, hardness tests for rigid plastics are performed in accordance with ASTM D785 (Ref. 5). Results are usually reported in terms of R scale or M scale readings, although full hardness scale (R, L, M, and E) capability may be employed as appropriate. For softer plastics that require a scale less than R, testing is performed by using ASTM D2240 (Ref. 6). Within ASTM Method D2240 Scales A and D are used to determine the indentation hardness of softer and harder materials, respectively.

Other ASTM hardness test methods are available but are recommended for production use. For reinforced and unreinforced rigid plastics, ASTM D2583 (Ref. 7) is used. This test method is based on a portable impressor and is used for production control. ASTMs D530 (Ref. 8) and D1415 (Ref. 9) are alternate methods recommended for testing rubber compounds.

Testing for hardness in plastics design should be conducted solely in accordance with ASTMs D785 (Ref.

5) and D2240 (Ref. 6). These test methods provide procedures for the full range of hard to soft plastic materials. Testing should include the specimen identification parameters (Table 1-2), test parameters (Table 2-4), and those parameters unique to the method, which are

1. *Hardness*. The average value determined by the Rockwell and/or durometer methods

2. *Hardness Scale*. The letter designation that indicates the Rockwell or durometer scale used for the hardness value

3. *Procedure*. For Rockwell hardness, the test procedure (A or B) should be used.

4. *Temperature*. Testing should be limited to 23°C (73°F).

5. *Specimen Thickness*. The test specimens should be at least 6.1 mm (0.24 in.) thick as a standard.

6. *Indentation Hardness Time*. The time in seconds associated with the load test procedure, as defined in each test method.

The value of hardness is used as a relative quantitative measure to compare materials (Ref. 10). As shown in Fig. 7-1, the scales overlap, and some materials may be measured on more than one scale. Testing a group of materials on the different scales may also result in plastics being ranked in different orders (Ref. 4). This possibility is one limitation of hardness testing. Also to equate the hardness scales based on hardness data is difficult due to this inconsistency. Thus Fig. 7-1 contains a relative indication without numeric association.

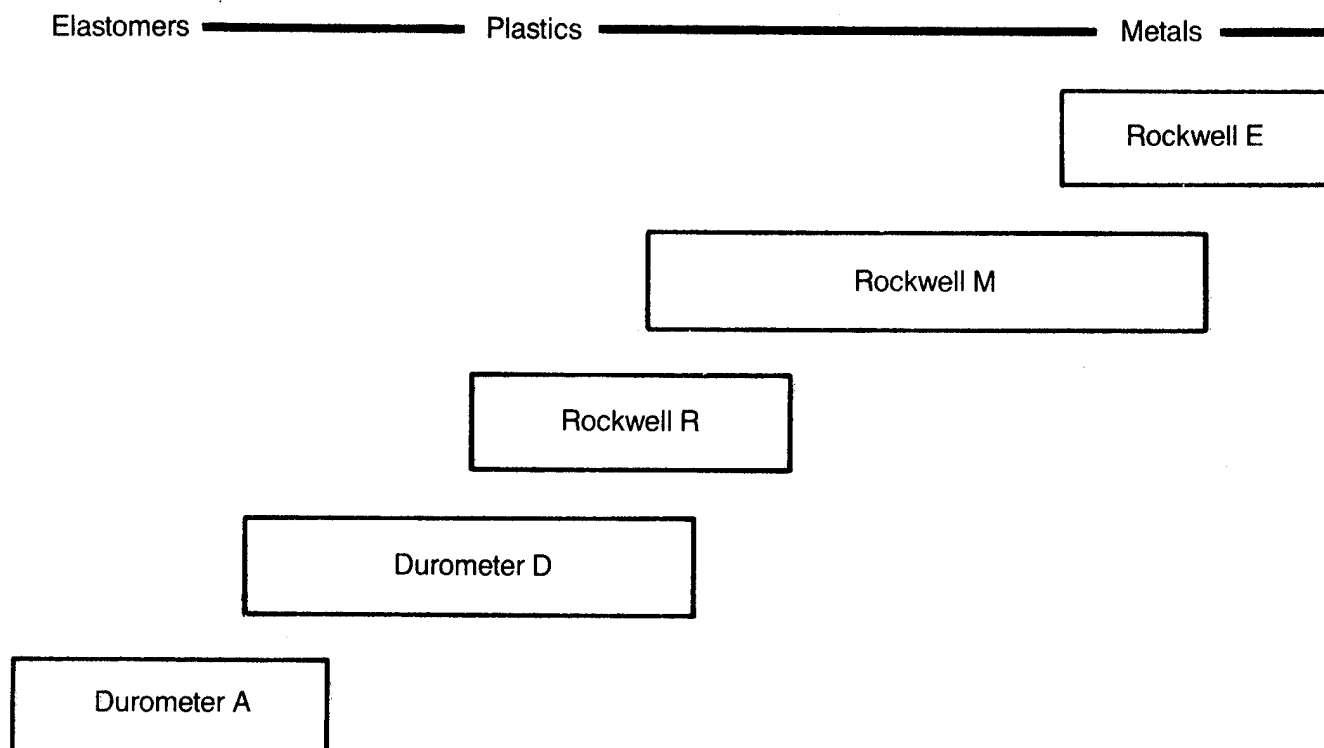


Figure 7-1. Relative Hardness Schematic

7-3 SURFACE PROPERTIES

The resistance of plastic materials to wear is a complicated phenomenon related to the surface characteristics and inherent mechanical properties of the material. The coefficient of friction and hardness values are indicators of the wear properties, but in no way can they be used to predict wear.

Wear is defined as a progressive loss of material due to the ploughing grooves created as a hard material is passed across a softer material (Ref. 11). On a microscopic scale it is the tearing away of material to form ridges or grooves. Normally wear is associated with bearings, gears, and thrust washers where a contact force is applied continuously to these items.

Wear resistance has also been measured in terms of abrasion and scratch resistance. Each is unique to the form of load application. Abrasion is a wearing away of material as occurs on flooring, whereas scratching is associated with scuffing the surface of transparent or high-gloss opaque materials.

For plastics the most widely used laboratory test methods pertain to abrasion, scratch, and wear resistance. These methods are discussed in pars. 7-3.2, 7-3.3, and 7-3.4.

7-3.1 COEFFICIENT OF FRICTION

Friction is the resistance that occurs when one surface slides over an adjoining surface. The coefficient of friction is defined as the ratio of force of sliding friction to the normal force pressing the surfaces together.

$$\mu = \frac{F_f}{F_n}, \text{ dimensionless} \quad (7-1)$$

where

F_f = forces of sliding friction, N (lb)

F_n = normal force pressing surfaces together, N (lb).

These forces are shown in Fig. 7-2. Although some plastic applications require high resistance, i.e., high coefficient, to movement, most applications require minimal resistance, i.e., low coefficient, to movement. An

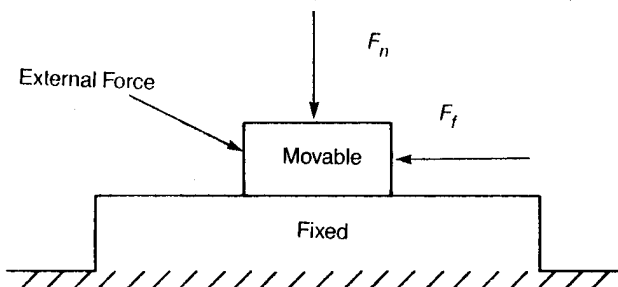


Figure 7-2. Friction Coefficient

example of applications requiring minimal resistance is bearings. For bearings consideration of the frictional behavior is extended to the phenomenon of wear resistance, which measures a time-dependent loss of material. The friction coefficient is a measure of the slip property of one material over another.

There are three types of frictional coefficients, namely, static, kinetic (dynamic), and rolling. The static friction coefficient is determined from the frictional force that resists motion between two surfaces at the point of impending motion. When a constant sliding motion is established, the friction coefficient is defined as dynamic. In most cases the frictional resistance to impending motion (static) is higher than the sliding resistance; this relationship results in higher values for the static frictional coefficient.

Rolling friction, as applied to rolling balls or cylinders, is a special form of resistance to motion and is the result of the inelastic deformation of the plastic material during the rolling process (Ref. 12). This phenomenon is treated theoretically but is not generally evaluated in a practical test. No existing ASTM test method evaluates rolling friction.

The coefficient of friction is not a material constant. It is highly dependent on the surface roughness and the applied load and is influenced by environmental factors such as temperature, humidity, and the presence of fluids or foreign particles. These factors complicate determination of the friction coefficient.

Although theoretically independent of the area, the real area of contact may be a factor. Also elastic deformation, plastic flow, and junction formation are concerns. To obtain practical data, every attempt must be made to reduce the influence of these factors in the test procedure because elaborate facilities would be required to evaluate their influence.

ASTM test methods D1894 (Ref. 13) and D3028 (Ref. 14) are available to determine the friction coefficient. The two methods differ markedly in their method of evaluating frictional resistance.

ASTM D1894 (Ref. 13) is a simplified method that employs a means of relative motion between a sled and a plane. A driving mechanism is started, and the initial maximum reading of frictional force before motion occurs is obtained to derive the static coefficient of friction. The frictional force after motion starts is obtained to derive the kinetic coefficient of friction; thus, both frictional values, static and kinetic, are determined in this test.

ASTM D3028 (Ref. 14) was developed to determine the kinetic coefficient of friction by using a large, rotating wheel against a small, fixed wheel. This test method allows measurement of the friction coefficient at continuously varying velocities (Procedure A) or between 0.10 to 3.00 m/s (0.33 to 9.84 ft/s). It also enables measurement at a constant velocity (Procedure B) of 1.00

m/s (3.28 ft/s) to determine the influence of time.

Of the two test methods, ASTM D3028 (Ref. 14) should be used to determine the coefficient of friction. Although this test method is used to determine the kinetic coefficient, it can also be used to measure the static coefficient (Ref. 12).

ASTM D3028 (Ref. 14) should be employed to determine the kinetic coefficient of friction for similar and dissimilar materials. The rotating wheel employs the plastic under evaluation, and the fixed specimen the same material or dissimilar materials. Stainless steel, brass, and aluminum should be used for dissimilar metallic materials. All testing should be performed without lubrication of any type. Testing should include specimen identification parameters (Table 1-2), the common test parameters (Tables 2-4), and those parameters unique to the test, which are

1. *Kinetic Friction Coefficient.* The average value of the coefficient of friction for each velocity increment or for the respective time increment, as required in Procedure A or Procedure B, respectively

2. *Velocity.* The increments of distance with respect to time for use in Procedure A should be 0.25, 0.50, 1.00, 2.00, and 3.00 m/s (0.82, 1.64, 3.28, 6.56, and 9.84 ft/s); for Procedure B the velocities of 1.00 and 3.00 m/s (3.28 and 9.84 ft/s) should be used. For procedure A the ascending and descending values should be noted accordingly.

3. *Time.* The elapsed time from the test start to the

stabilization of the frictionometer readings at a constant value, as required in Procedure B

4. *Normal Force.* The value of the force equal and opposite to the weight of the load employed for the material under evaluation

5. *Temperature.* The test temperature should be limited to 23°C (73°F).

Data generated for the coefficient of friction as a function of velocity shown in Fig. 7-3 fulfill a void in many engineering applications, e.g., bearings, cams, and gears. Graphical presentations permit the comparison of materials.

7-3.2 ABRASION RESISTANCE

The resistance of a material to abrasion is a form of wear resistance that results from mechanical forces acting at the surface. Tests for abrasion resistance are severe—they employ a hard, inorganic material (sandpaper) as the abrasive. Generally, the relative resistance of materials is measured by the resulting weight or volume loss of material.

Although abrasion resistance is principally associated with flooring, tires, and other rubber products, the data are useful in military applications. They may be used as a relative measure of resistance to handling, cleaning, and other abrasive environments.

A number of abrasion testing machines for polymers have been developed over the years, but the two abraders described in ASTM D1242 (Ref. 15) are used most often.

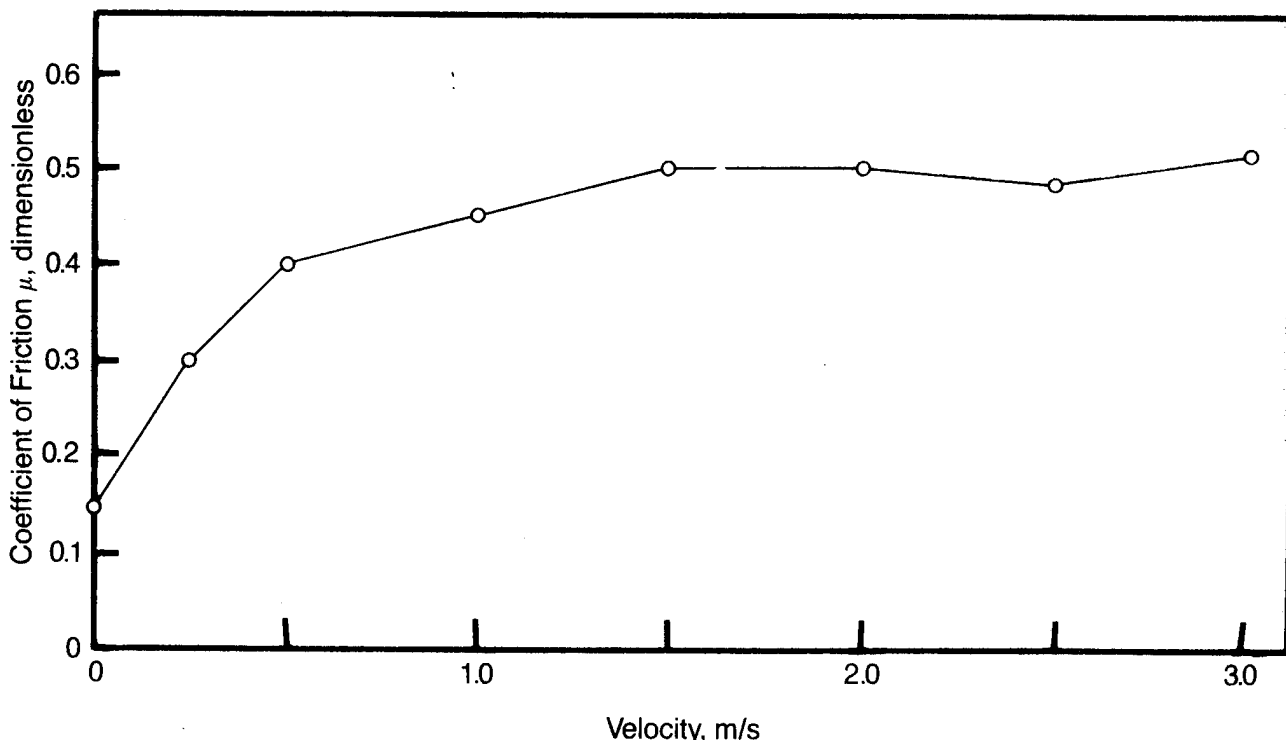


Figure 7-3. Friction Coefficient vs Velocity

One abrader employs a loose abrasive, and the other, a bonded abrasive.

The bonded abrasive unit described in ASTM D1242 is also known as the Armstrong Abrader (Ref. 16). It abrades the material surface by constantly applying clean sandpaper to the surface of the specimen. This means of evaluation is preferable because of the absence of loose plastic particles to clog the abradant and the fact that there is no abradant wear. Also this method minimizes the effect of temperature.

Another device used to abrade plastic surfaces is described in ASTM D1044 (Ref. 17). The device is called a Taber Abraser, or Abrader, and its purpose is to abrade transparent surfaces to obtain a relative indication of the effect on optical properties. The Taber Abraser was not designed to determine weight loss, but because of its ease of use, it could be used for this purpose (Ref. 18).

Abrasion resistance data are intended to provide a relative measure of plastic resistance to an abrasive. Correlating these laboratory data with actual use data is difficult. The difficulty is due to the many variables, the various test techniques, and the intricacy in matching the mode of abrasion found in practice. The materials themselves vary in that their surface texture and use of fillers (reinforcements) influence the abrasive characteristics.

Testing for abrasion resistance should be performed in accordance with ASTM D1242 (Ref. 15) by using the Armstrong Abrader (Method B). Testing should include specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test, which are

1. *Volume Loss.* The average volume loss in cubic centimeters (cubic inches), as calculated from the weight loss, divided by the density of the material being abraded

2. *Number of Cycles.* The nominal number of cycles should include 100, 250, 500, and 1000.

3. *Temperature.* The test temperature should be limited to 23°C (73°F).

4. *Carriage Load.* The carriage load should be 133.4 N (30 lb).

5. *Abrasive Tape.* The type of abrasive tape (coarse or fine) and its associated brand name and grade. Testing with both coarse and fine tape is preferred.

The test results provide a plot of the volume loss versus the number of cycles at ambient temperature, as shown in Fig. 7-4. This plot, in turn, provides an indication of the resistance of abrasion (loss) with use (cycles). It also provides a relative measure of resistance when compared with the plot of other materials. The test, however, has little design value in predicting wear. Wear resistance can be determined only with a simulated test procedure that approximates end use conditions (Ref. 19). Although other properties, such as tensile strength, tear strength, and hardness, are related to performance, there is no direct correlation with the abrasion data.

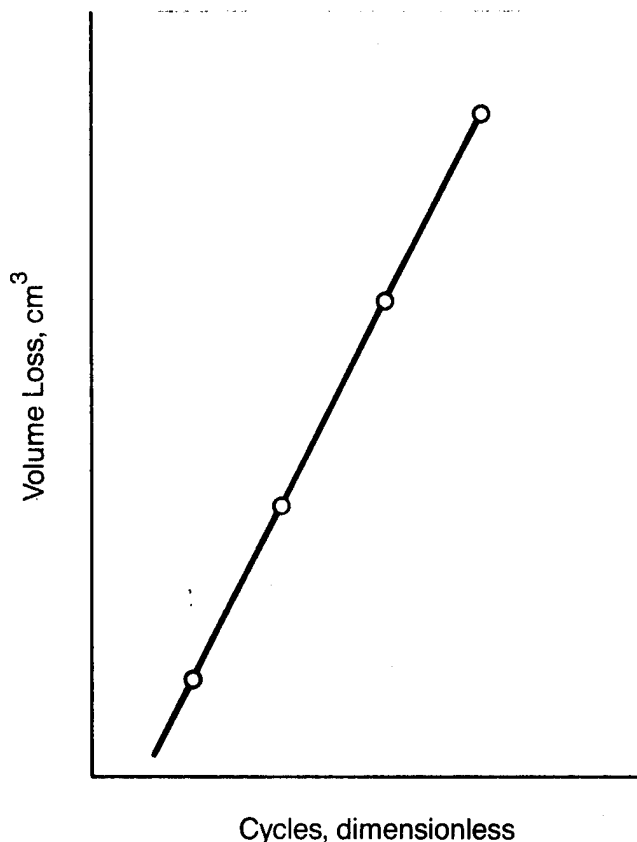


Figure 7-4. Abrasion Resistance

7-3.3 SCRATCH RESISTANCE

Measurement of the resistance of plastics to scratching is not formally covered by an ASTM test method. However, ASTM D1044 (Ref. 17) covers the surface abrasion of transparent materials, as discussed in par. 7-3.2, and is an appropriate method. This method is, however, limited to transparent materials because the test measures the change in haze as a function of exposure to the Taber Abraser.

Another standardized test method that indicates resistance to scratches at the surface is ASTM D673 (Ref. 20), which was established to typify mild, airborne abrasive particles encountered in actual use. The method measures the change in gloss as an abrasive is dropped from a fixed height. The gloss measurement is made in accordance with ASTM D523 (Ref. 21).

ASTM D673 (Ref. 20) is an all-encompassing test method because it is applicable to opaque materials; therefore, it is a more useful indication of scratch resistance than ASTM D1044 (Ref. 17) and should be used in all testing. Testing should include the specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those parameters unique to the test, which are

1. *Gloss.* The initial specular luster and the luster after exposure to the various amounts of abrasive

2. *Geometry*. The angle of measurement of gloss should be 60 deg.

3. *Abrasive*. The No. 80 silicon carbide abrasive as specified in the standard should be used.

4. *Abrasive Weight*. The amount of abrasive in grams (pounds) used for each test point

5. *Temperature*. The test temperature should be limited to 23°C (73°F).

The mar resistance test is only an indication of the plastic resistance to scratching. A plot of change in gloss versus the amount of abrasive permits the relative comparison of plastic materials.

The fact that the scratch resistance for a plastic may be poor does not necessarily imply poor abrasion resistance or volume loss of a material. Some low-hardness plastics are easily scratched yet may have a small abrasion loss by volume.

7-3.4 WEAR RESISTANCE

In the study of wear, or tribology, an attempt is made to predict the progressive loss of material attributable to the relative motion between two surfaces. Although there are theoretical developments for wear of plastics, none has been sufficiently developed to assist in making this prediction (Refs. 22 and 23). The prediction of wear is difficult because of the complexity of load, contact area, speed, and temperature effects. Other material variables are friction coefficient, hardness, and strength. The net result of these problems is reliance on tests to duplicate end use conditions.

Wear behavior of plastics on plastics is defined as "adhesive wear", which is characterized by removal of small plastic particles from the surface. This behavior contrasts with so-called "abrasive wear", which is characterized by occurrence of melting or gouging of the material. Information for both types of wear is needed by design engineers.

The characteristics of adhesive wear for the various material combinations have been derived empirically. Experimentation is performed principally with a thrust washer design configuration and apparatus to determine the wear factor (Refs. 24 and 25). Generally, however, the results of this type of test are not applicable to other design configurations.

Although wear data are being developed by using the thrust washer device, no standard test procedure has been established by ASTM. This fact indicates the area is still in need of further development.

The progressive volumetric loss of material as experienced in adhesive wear can be aggravated by excessive loads or velocities; this occurrence results in severe loss of material through gouging. One of the methods used to screen materials involves the use of PV values. The PV value, or factor, is the product of the contact pressure P

and the surface velocity V and is used to assess relative suitability when compared to the limiting PV value.

The PV limit is a critical point at which a recognizable change in bearing performance occurs. When the PV limit is exceeded, the material will change from mild to severe wear, undergo plastic flow, encounter unstable friction, or result in abrasive-type wear, i.e., melting or gouging. Lubrication, ambient temperature, clearances, and surface roughness affect data. Also PV data based on short-term, intermittent testing may not be indicative of long-term, continuous operation.

PV experimentation has been performed by using either journal-bearing or thrust-bearing configurations. Although this practice appears to be a well-accepted method for material evaluations (Refs. 26, 27, and 28), no standardizing document has been promulgated.

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CHAPTER 8

PERMANENCE PROPERTIES

The permanence characteristics discussed in this chapter are addressed in general terms and represent the common environmental factors most important for use in materials characterization. Each permanence property is discussed in detail, and the appropriate test methods, data parameters, and engineering significance are indicated.

8-1 INTRODUCTION

The term "permanence properties", although somewhat of a misnomer, is used to indicate the resistance of a given property to a deteriorating influence. The classification is addressed in the American Society for Testing and Materials (ASTM) *Annual Book of Standards* (Ref. 1), which lists a number of test methods used to determine the influence of specific environments on plastic properties. These environments typically involve exposure to chemicals, water, heat, and weather, and when exposure is over extended periods of time, these environments become permanence factors. Thus when addressed from the perspective of long-term exposure, temperature becomes a permanence factor.

Testing for permanence characteristics or degradation should be included in all material assessments as a standard procedure. This amount of testing generates large amounts of data, which are essential to the material selection process. Many material suppliers evaluate and record a variety of permanence data; however, more uniform testing and reporting are necessary for this mass of information.

The test methods described in this chapter are essential to the characterization of all plastic materials. Each test method contains criteria that should be specified. The comprehensive data indicate the ability of a material to perform its intended function in the environment and time frame evaluated. Although this testing will not indicate suitability in the product configuration, it will significantly improve the screening process during the selection of materials.

The permanence characteristics described in this chapter emphasize the environmental variables and associated test criteria. The deteriorative effects are usually determined in relation to mechanical properties, dimensional changes, and appearance because these characteristics reflect basic material integrity. Electrical and optical properties should be evaluated only for those materials for which environmental effects are suspected to cause degradation.

The permanence properties described in this chapter have been classified occasionally according to how they

change during environmental exposure. When chemical interactions that occur during exposure result in a permanent change of chemical interactions (Ref. 2), the interactions should be addressed as chemical properties.

All environmental factors involve exposure for extended periods of time; therefore, they may also be classified as aging properties. The chemical and aging properties are discussed in pars. 8-1.1 and 8-1.2 to provide a basis for the properties addressed in this chapter.

8-1.1 CHEMICAL PROPERTIES

Because they are organic compounds, plastic materials are generally affected by exposure to chemical compounds. The severity of the effect, however, is dependent on the chemical and the environmental conditions present. Changes may be permanent because of chemical interaction that results in permanent change of the plastic, or they may be temporary, in which case evaporation of an absorbed chemical may restore the plastic to its original physical condition.

Although the term "chemical properties" has sometimes been used to indicate any effect that results in a chemical change within a plastic structure, it is more appropriate to classify chemical properties as those responses by material to exposure to chemicals. In many chemical-plastic interactions, an actual chemical change in material structure does not result. In this chapter the term "chemical resistance" (par. 8-2) describes chemical response, and it is the accepted term throughout the industry.

In assessments of chemical resistance, exposing plastics to various chemical reagents, e.g., acids, alcohols, and other organic compounds, is common practice (Ref. 3). Testing includes distilled water as an isolated reagent primarily to isolate the influence of water when tests are done with various chemical solutions. Thus chemical resistance testing also incorporates the influence of water on plastic properties.

Traditionally, water has been tested separately in terms of water absorption and water vapor transmission, which are discussed in pars. 8-3 and 8-4, respectively. These properties do not involve degradation but are considered essential to all plastic assessments.

Gas permeability is another property that may be associated with the term "chemical properties". Its importance is quite apparent in thin-film technology. ASTM Test Method D1434 (Ref. 4) provides for determination of the steady state rate of transmission of a gas through plastic, film, sheeting, or laminates. The emphasis of this handbook is on molded forms of plastics, so gas transmission or permeability of films has not been included.

8-1.2 AGING

The term "aging" refers to the effect on materials of exposure to atmospheric conditions experienced on a daily basis for an interval of time. In this context three specific aging conditions have been defined: (1) natural aging, (2) heat aging, and (3) weathering. These three conditions are described in pars. 8-5 through 8-7. Aging properties provide fundamental information of material behavior that is needed for most applications.

Exposure to elevated temperatures—heat aging—is of concern for plastics because many materials readily degrade in this environment. Generally, changes in structure do not occur at low temperatures; therefore, low-temperature aging is not addressed. At low temperatures molecular motions are minimal; it must be remembered, however, that material response does change at low temperatures, i.e., limited molecular motion causes differing material properties.

Accelerated testing for aging is a form of material exposure conducted within the laboratory and is intended to simulate outdoor weathering conditions. Such tests expose plastic specimens to combinations of ultraviolet light, water, and heat. The results obtained from many test methods are not intended to correlate with actual weathering conditions because of the variability of test parameters with geographic location (Refs. 5-8). Because the accelerated data do not correlate satisfactorily, the test methods are not recommended for testing of all plastic materials.

8-2 CHEMICAL RESISTANCE

Plastic materials are noted for their markedly different responses to chemicals. Although many are recommended for their superior chemical resistance, all plastics are susceptible to some form of time-dependent change or degradation, which depends on the chemical and the environment.

For the product designer the principal question is how the material will behave in the end use environment. Once the technical requirements are established, a review of technical data enables the designer to select the materials that are potentially suitable for use. Of course, the final assessment can be made only following an evaluation of the product itself because chemical resistance data

developed within the laboratory provide only an indication of performance.

Traditionally, chemical resistance testing has been viewed as determination of the response of a specimen when immersed in a solution. There is very little data on the effects of vapors emanating from either the solid or liquid chemical contaminants. This environment, however, is important because plastic components are sometimes confined in closed areas in the presence of chemical vapors or are exposed to outdoor industrial contaminants.

Testing of plastics to attack by chemicals must include complete descriptions of both the plastic and the chemical. Each plastic evaluated must be identified by trade designation because composition, fillers, and plasticizers vary widely among suppliers and grades of a single plastic type. The chemical compounds should be identified as standard reagent grade or by common designation.

The severity of chemical attack on plastics ranges from no effect, an appearance change (discoloration, loss of gloss, etc.), a dimensional change, a loss of mechanical strength, a fracture, to dissolution. These responses are greatly influenced by temperature, stress, and time (Ref. 9). Thus it is imperative that these three parameters be considered in chemical resistance testing.

The chemical resistance of plastic is reported in the manufacturer's literature or test reports in a number of ways. Many material suppliers publish literature containing data specifying resistance in qualitative terms, i.e., "excellent", "good", "fair", "poor", "not recommended", or "unacceptable". Another approach is recommending use up to a specific temperature by means of a bar graph or by indicating an upper temperature limit. Although both presentations consider time and temperature, they are inadequate (Ref. 10) for engineering use because (1) the basis upon which the recommendation is made is not provided and (2) the terms used to justify the recommendations are ambiguous. Specific test data upon which the user can make a performance judgment are required because the degree of change acceptable to one designer may be unacceptable to another.

A common method of reporting data is to record changes in appearance, dimensions, weight, or hardness. These data are satisfactory provided the product will encounter no mechanical loads because the data reflect only change in the specimen surface and indicate only absorption of the chemical. The data are, however, not sufficient for an effective material assessment. Much of the chemical resistance data produced are based on dimensional and weight changes due to low cost and ease of measurement.

Mechanical property data reported for plastics have been mainly the result of evaluating the change in ultimate strength, elongation, and modulus of elasticity. These changes, following the immersion period for the specimen, are generally expressed as percent loss or

percent retention and are by far the most meaningful data for engineering use. A reduction in values indicates loss of structural integrity and/or embrittlement, whereas an increase in values reflects plasticization through absorption of the chemical.

Testing for mechanical properties has centered on tensile, compression, and flexural properties (Ref. 11). For engineering use tensile properties are the more meaningful and should be evaluated accordingly, whereas testing in compression and flexure is considered excessive and needless.

Testing for permanence under constant tensile stress is an extremely important test for product development. Inevitably, all materials will undergo external loading or will encounter thermal stresses. If not, they may contain molded-in stresses that could lead to product failure. This possibility necessitates the conduct of crazing or stress-cracking-type testing in chemical environments to complete the chemical resistance information.

The absence of fully characterized data hinders product development; it forces the designer to extrapolate or conjecture as to product performance and demands initiation of independent testing programs. Appropriate and accurate test data are essential.

Tensile property changes that occur following no-load exposure are the most significant in ascertaining the effects of chemical attack. Evaluation of tensile changes that follow periods of induced stress has been performed, but such evaluation is not essential to isolate the effects of water when used in aqueous solutions. It is necessary, however, to test identical specimens by immersion in water. Comparison of tensile data with the results of water immersion reflects the influence of the water on degradation. Also test methods are available to evaluate the resistance of plastics to staining. These test conditions are considered special and therefore are not included in this handbook.

Laboratory testing for chemical resistance has been based on ASTM Test Method D543 (Ref. 3). Although this test method states that it is suitable for all plastic materials, ASTM has also established ASTM Test Method C581 (Ref. 12) for thermosetting resins. This test method, used to evaluate thermosetting resins for use in reinforced plastic structures, offers no advantage over ASTM D543 (Ref. 3) except to specify material requirements. ASTM C581 (Ref. 12) recommends determination of property changes described in ASTM D543 (Ref. 3). For standardization purposes all testing should be performed in accordance with ASTM D543 (Ref. 3), as stated in the paragraph that follows.

Chemical resistance testing should include provisions for reporting changes in weight, dimensions, appearance, and strength. ASTM D543 (Ref. 3) provides for these parameters and includes the use of standard tensile test procedures; also ASTM Test Method D638 (Ref. 13) is

implied. ASTM D638 (Ref. 13) does not, however, specify testing for the influence of constant stress. It is necessary that ASTM give consideration to a stress environment test that will either modify ASTM D543 (Ref. 3) or promulgate another test method. In the interim all testing for changes in tensile properties should be performed with ASTM D638 procedures, Type I or IV specimens, and a test speed of 5 mm/min (0.2 in./min) in conformance to the data established in par. 3-4.1.

Chemical resistance under constant stress is an extremely important variable used in material assessments. Although the method of inducing constant stress for an immersion has not been included in this handbook, test procedures have been developed (Ref. 10) to induce tensile strain for evaluation of chemical stress cracking. The induced tensile strain may be in direct tension or may result from a bend test (flexure).

Testing results for chemical resistance should report the appropriate specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those unique parameters, which are

1. *Weight Change.* The average percent change in weight for the material after the exposure period as compared to the average weight of the specimen before exposure

2. *Dimensional Change.* The average percent change in diameter, length, width, or thickness after the exposure period as compared to the average dimension before exposure

3. *Appearance.* The general appearance of the specimen after the exposure period in terms of discoloration, warping, flaking, pitting, swelling, or other apparent changes

4. *Tensile Property Change.* The average percent change in ultimate tensile strength, ultimate elongation, and modulus of elasticity as compared to control specimens stored in a conditioned environment

5. *Time.* The exposure time in days, which should be 7, 30, 180, or 360 days. Exposure times up to two yr or more are preferred.

6. *Temperature.* Testing should be performed at 23°, 50°, and 100°C (73°, 122°, and 212°F) and up to the reagent boiling point.

7. *Stress Level.* The level of applied stress in megapascals (pounds per square inch) and the mode of loading, tensile or flexure. Testing should be performed at three stress levels and at elevated temperature.

8. *Specimen Thickness.* The thickness of all specimens should be 3.2 mm (0.13 in.).

9. *Concentration.* The percent by weight of the chemical in an aqueous solution.

Combinations of concentration, temperature, and stress levels for each material are implied in the given criteria. If a material suffers severe degradation or dissolves in short periods of time at low temperature, testing should be

discontinued. To facilitate testing, appearance, weight, and dimensional changes may be measured for specimens used in tensile testing.

The test criteria for chemical resistance result in data that reflect the change in a material immersed in a chemical reagent, with respect to variations in concentration, temperature, stress level, and time. The percent change in appearance, weight, dimension, strength, and resistance to an induced stress can be plotted as a function of any of these variables. Although data compiled to such a degree is very meaningful, they are still principally used to screen materials for end use applications. The determination of material suitability for an application rests with the designer and the end use requirements. The degree of acceptable degradation must be determined. Data provided by material suppliers and presented in terms of satisfactory or unsatisfactory are not appropriate for use.

8-3 WATER ABSORPTION

Exposure of plastics to moisture environments may result in an increase in water content because of absorption. Plastics absorb varying amounts of water, and this absorption may alter plastic properties—particularly mechanical and electrical—in different ways. Besides direct immersion, water may also be absorbed in high-humidity environments. Because the effect of water absorption is usually detrimental, it should be considered when comparing materials.

Plastics that absorb relatively large amounts of water tend to expand, and expansion is important if dimensional stability is critical. Electrical and mechanical properties are noticeably affected by moisture. If a material is known to absorb moisture, the influence on electrical properties must be assessed.

Absorption of water by plastics is a time-dependent phenomenon that varies with temperature and thickness (Ref. 14). All materials will absorb moisture until an equilibrium point is achieved, i.e., the point at which no significant change occurs with further exposure. Equilibrium may occur in days in boiling water, or it may take years in standard temperature and humidity conditions.

Desorption, or loss of moisture, is a behavior unique to some plastics when they are exposed to very dry conditions such as those in a desert environment. This drying can result in dimensional change and significant material property changes that affect performance of military hardware. Plastics that absorb significant amounts of water should also be evaluated at a dry, or near-zero, moisture content to determine the effect of the absence of water in the material.

Water absorption by plastics is evaluated in accordance with ASTM Test Method D570 (Ref. 15). The method is limited to the determination of the relative rate of water absorption (percent weight change) when the plastic is

immersed in water at ambient and elevated temperature. If a plastic exhibits high moisture absorption, the test method may be used as a guide to the effects of water exposure on properties. To facilitate data generation when ASTM Method D570 (Ref. 15) is employed, the dimensional change should be measured concurrently with weight determinations.

For those materials predisposed to significant water absorption, testing should be performed at varying humidity conditions to assess the time and equilibrium level. These additional technical data are pertinent for material to be deployed in this common end use environment.

Testing for water absorption in accordance with ASTM Test Method D570 (Ref. 15) should include the appropriate specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those unique parameters, which are

1. *Specimen Thickness.* All testing should be performed with specimens of 3.2 mm (0.13 in.) in thickness.
2. *Time.* The exposure time in hours. Testing should be performed at 2, 24, and 168 h and at two-week intervals until equilibrium is achieved.
3. *Weight Change.* The average percent change in weight for the exposure period, as compared to the average weight of the control specimens
4. *Dimensional Change.* The average percent change in diameter, length, width, or thickness after the exposure period, as compared to the average dimension of the control specimens
5. *Appearance.* Any observed change in appearance, such as warping or cracking, during the exposure period
6. *Immersion Temperature.* Testing for water immersion should be performed at 23°, 50°, and 100° C (73°, 122°, and 212° F).
7. *Humidity Exposure.* Materials having high moisture absorption should also be tested at 50 and 95% relative humidity at 23° C (73° F).

Evaluation of water absorption for plastics, as established in the foregoing test criteria, indicates the relative percent weight gained as a function of time for the immersion period. Plastics showing a significant weight gain, i.e., from between 3 to 10%, manifest dimensional changes. Weight changes of less than 1% generally indicate no dimensional change or no effect.

Although water absorption is a function of thickness, testing at various thicknesses is not essential. Thicker or thinner materials absorb moisture at different rates, but all approach comparable equilibrium points. Occurrence of significant changes means that the influence of moisture content on both electrical and mechanical properties must be assessed. Thus the test data identified in Chapters 3 and 4 must be evaluated with moisture as a variable.

The data generated for water absorption produce plots of percent weight and dimension change as a function of

time for both immersion and humid environments. These data also provide a comparison with other materials in the screening of plastics for end use.

8-4 WATER VAPOR TRANSMISSION

The water absorption characteristics described in par. 8-3 are associated with the transmission of water vapor through plastic materials, which is important in military applications because hardware is commonly exposed to high-humidity environments and unwanted water may result in problems.

Water vapor transmission (WVT) data indicate the steady state water vapor flow in unit time through a unit area of body. WVT data are generally expressed as the mass of water in grams (pounds-mass) that passes through a square metre (square foot) of film or sheet material each hour. Environmental parameters that also affect the rate of transmission are the vapor pressure, temperature, and humidity conditions at each surface.

The WVT rate is also influenced by the atmospheric water vapor or the plastic in direct contact with water. Because water contact is reasonable to expect of material in service, it is considered a factor in testing for the rate of water vapor transmission. ASTM Test Method E96 (Ref. 16) uses a water method that determines the rate of vapor movement from the water to a controlled atmosphere.

Water vapor permeability is a term also used to describe transmission of water vapor. It differs from WVT because it is based on a unit thickness of material. Average permeability is calculated only when the test specimen is homogeneous and not less than 12.7 mm (0.5 in.) thick (Ref. 16). Materials of interest in this handbook are primarily of lesser thickness; therefore, permeability calculations are not considered.

Testing for WVT should be performed in accordance with ASTM Test Method E96 (Ref. 16) and should include the appropriate specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those unique parameters, which are

1. *Water Vapor Transmission.* The average rate of water vapor transmission in grams per square metre per hour (pounds per square foot per hour)

2. *Temperature.* The average temperature of the test environment. Testing should be at 23° and 32°C (73° and 90°F).

3. *Humidity.* The average relative humidity of the test environment. All testing should be performed at 50% relative humidity.

4. *Procedure Testing.* Testing should be performed in accordance with Procedures B, BW, and D. Procedures B and BW differ; in Procedure BW water contacts the specimen by inverting the dish/specimen assembly. Both procedures test at 23°C (73°F). Procedure D is the water method to be used at 32°C (90°F).

5. *Thickness.* The average thickness of the test specimen. All test specimens should be 1.6 mm (0.06 in.) thick.

WVT data are useful for those end use applications in which water penetration would be detrimental. Typical examples of such applications are sealed electronic circuitry, propellants and explosive devices, and enclosed mechanical devices.

WVT data are useful in comparing the relative rates at which water vapor passes through a finite thickness of plastic. Although the testing is intended mostly for permeable and semipermeable materials, it is considered essential for all materials. For those materials that do not readily absorb moisture, the WVT can be expected to be minimal. WVT data are measured in terms of a mass change with time and are calculated in terms of grams (pounds-mass) of vapor that pass through a square metre (square foot) of material in 24 h.

The fact that WVT data vary with other exposure conditions will be considered as test data for WVT are developed for standard laboratory atmospheric conditions. The data, however, will indicate the need to continue to pursue either laboratory testing or evaluation in the end use environment.

8-5 NATURAL AGING

As used in this chapter, the term "natural aging" defines the degree of change to a plastic under standard laboratory conditions. The data are intended to indicate permanence characteristics when a plastic is exposed to a temperature of 23°C (73°F), a relative humidity of 50%, ambient pressure, and protection from ultraviolet light sources. This type of data categorizes the most basic form of aging and should be the basis for all other aging tests.

To evaluate permanence characteristics, testing normally includes control specimens that are evaluated with those exposed to the specific environment. The difference in the property level evaluated is calculated as percent change and is determined as that change in the property after exposure as compared to control specimens exposed for the same exposure period. The control specimens are those stored under standard laboratory conditions.

If control specimens are tested at the beginning of any exposure period, specimens tested at any time duration can be compared with the original specimen. This comparison would, in essence, indicate the natural aging characteristics. Although no formal ASTM test procedure exists to evaluate natural aging, it should be evaluated; therefore, a test procedure should be promulgated for this purpose. In the interim existing permanence tests should be used to establish natural aging data. However, because a test procedure designed specifically for natural aging is nonexistent, appropriate alternative procedures should

be specified. ASTM Test Method D618 (Ref. 17) should be used to establish the natural aging environment, i.e., the standard laboratory atmosphere. The test environment should exclude ultraviolet radiation or other deleterious factors.

ASTM Test Method D638 (Ref. 13) should be used for property evaluation because it will enable determination of percent change in tensile properties. Testing should include the specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those unique parameters, which are

1. *Temperature.* The standard laboratory temperature of 23°C (73°F)

2. *Humidity.* The standard relative humidity of 50%

3. *Time.* The exposure time in days should be 180, 360, 540, 720, and yearly thereafter up to 10 yr, as appropriate.

4. *Appearance.* The general change in specimens as compared to control specimens

5. *Tensile Property Change.* The average percent change in tensile strength, elongation, and modulus of elasticity, as compared to control specimens. Testing should be performed in accordance with ASTM D638, as outlined in Chapter 3, by using a test speed of 5 mm/min (0.2 in./min) at a temperature of 23°C (73°F). Testing for impact should be performed at 23°C (73°F) in accordance with D3029, as described in Chapter 3.

6. *Dimensional Change.* The average percent change in diameter, length, width, or thickness after the exposure period as compared to the average dimensions of the control specimens.

Natural aging, as defined in this chapter, is intended to provide basic information on the integrity of a plastic when it is exposed to a standard atmospheric environment of the laboratory. The data on appearance, dimensions, and tensile properties serve two purposes. First, they provide the long-term response of a plastic in controlled conditions, i.e., within buildings, in air-controlled equipment, and in controlled depot storage configurations. Second, they provide a datum point from which all permanence effects can be assessed.

Testing for tensile properties at the one rate of loading, e.g., 5 mm/min (0.2 in./min) and a 23°C (73°F) temperature, indicates only the influence of time on specimen integrity. When a change is reflected in the strength, elongation, or modulus of the plastic, it indicates that other mechanical, electrical, or physical properties may be affected. This possibility should prompt additional investigations into the long-term performance characteristics.

8-6 HEAT AGING

Heat aging is a phenomenon whereby a material may undergo a permanent change over time when exposed to an elevated temperature. Although some plastics may deteriorate by oxidative degradation, in others the changes

may be only physical, i.e., they result from molecular reorientation, stress relieving, or an advance in polymerization. The severity of the temperature and the length of exposure determine the extent of change that may occur. Some plastics may not noticeably deteriorate from heat aging—a fact that is only ascertained through testing.

Interest in the heat aging characteristics of plastics has resulted in promulgation of a number of generalized test methods by ASTM. Two test methods, ASTM D3045 (Ref. 18) and D794 (Ref. 19), define exposure conditions for testing plastics at elevated temperature. Others, ASTM Test Methods D1204 (Ref. 20) and D1299 (Ref. 21), are used to measure dimensional change as a result of exposure to elevated temperatures. Also ASTM D1870 (Ref. 22) provides a procedure for exposure in a tubular oven. The intent of these test methods is to determine the change in a material after exposure to heat. Testing is always performed at ambient conditions for comparison with control specimens to arrive at an average percent change in material property.

Heat aging should be performed for all plastics primarily to assess the dimensional changes and changes in mechanical properties. Testing should be performed at a few temperature levels and always at minimum relative humidity. This testing condition may be met with an air-circulating oven capable of maintaining proper temperature control. Heat aging tests for other property changes should be performed on a special need basis. A number of other heat aging test methods developed by ASTM, e.g., discoloration and loss of plasticizer, are used to assess permanence effects. Although of value, they do not indicate material integrity as described in this chapter.

Heat aging tests should be limited to evaluating changes in ultimate strength, elongation, and/or the modulus of elasticity. A change in properties from those of the control specimens reflects the influence of heat on the plastic structure. The changes may be the result of a number of mechanisms: oxidative degradation, loss of plasticizer, loss of moisture, or secondary chemical reaction. All testing should be performed under no-load conditions in the hot-air environment to determine the influence of heat only.

In the interest of standardization, testing for heat aging should be performed in accordance with ASTM Test Method D3045 (Ref. 18). This test defines exposure conditions to determine degradation in a hot-air oven over extended periods of time. Testing for mechanical properties should be performed in accordance with ASTM D638 (Ref. 13). Testing results should indicate the specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those unique parameters, which are

1. *Temperature.* The exposure temperature should be 70°, 90°, 120°C (158°, 194°, 248°F), and higher, according to the limitations of the material.

2. *Time.* The exposure time in days should be 180, 360, 540, and 720.

3. *Relative Humidity.* The relative humidity should be at a minimum for all tests; less than 10% is suggested.

4. *Appearance.* The general change in specimens is compared to control specimens.

5. *Tensile Property Change.* The average percent change in tensile strength, elongation, and modulus of elasticity, as compared to control specimens. Testing should be performed with ASTM D638, as outlined in Chapter 3, by using a test speed of 5 mm/min (0.2 in./min) at a temperature of 23°C (73°F). Testing for impact should be performed at 23°C (73°F) in accordance with ASTM D3029, as described in Chapter 3.

6. *Dimensional Change.* The average percent change in diameter, length, width, or thickness after the exposure period, as compared to the average dimensions of the control specimens.

Heat aging data are intended to provide basic information for the integrity of a plastic exposed to elevated temperature. The change in appearance, dimensions, or tensile properties serves two purposes. First, it will indicate whether a material will suffer oxidative degradation or other form of deterioration. Second, it will enable comparison with other materials for suitability in high-heat environments.

Testing for tensile properties at the one rate of loading (5 mm/min (0.2 in./min)) used in most tests conducted as a standard and at 23°C (73°F) indicates only the influence of time on specimen integrity. A change reflected in the strength, elongation, or modulus of the plastic indicates that other mechanical, electrical, or physical properties may be affected. This possibility should prompt additional investigation into the long-term performance characteristics.

Although it is widely known that electrical and other properties are affected by heat aging, evaluation of these properties has not been suggested because the testing would be costly.

8-7 WEATHERING

Plastics are being increasingly used in outdoor environments. This exposure of plastics to natural atmospheric conditions is generally termed weathering or outdoor weathering. Direct outdoor exposure, which requires exposure periods of up to three years or more, is the most accurate method used to obtain a correct indication of weather resistance. Attempts to accelerate the atmospheric effects within the laboratory have provided acceptable reproducibility; however, due to the difficulty in accelerating the diurnal effects of sunshine, rain, wind, and dust, there is no artificial way to predict outdoor weatherability precisely.

Outdoor weathering testing usually is conducted at test sites that may vary from desert, seashore, industrial,

arctic, to tropical. The environmental factors at each site vary significantly. Consequently, data generated at one site and for one short period cannot be associated with another site and time period. Therefore, testing is necessary at more than one location. Traditionally, weathering tests by the Army (Ref. 23) have been carried out at three locations: Panama Canal (hot-wet), New Mexico (hot-dry), and New Jersey (temperate). Comparable locations used by industry include Florida, Arizona, and Massachusetts. These three climates are reasonable choices for testing all plastic materials. Extremely cold climates, like the Alaskan, are not used; they are not considered as severe as the other three types.

Testing for outdoor weathering of plastics is performed in accordance with ASTM Test Method D1435 (Ref. 24). The report requirements suggest reporting sunlight energy data and other climatic data, such as rainfall and temperature. In lieu of specifying detailed data, the location (city and state) and the dates of exposure should be sufficient for environmental identity.

The evaluation of specimens exposed to outdoor weathering is conducted on a comparative basis, and control specimens are used to determine the original and final control values. Property data at specific intervals generally reflect the percent change over time for the specific outdoor site.

The best way to assess outdoor weathering properties of all plastics is to evaluate the change in mechanical properties with exposure time. Testing for tensile and impact properties should be a sufficient indicator of long-term performance. Tensile properties have been effectively used as indicators by the US Army (Ref. 23).

Weathering effects on electrical and optical properties should also be evaluated for those materials normally used for either purpose. Dielectric strength, dielectric constant, and volume resistivity are used as electrical properties; transmittance and yellowness index are appropriate optical properties. These mechanical, electrical, and optical properties are not evaluated for direct use in design; they are used to indicate a relative level of degradation. If deterioration is observed, other weathering tests may be required to assess end use acceptance.

Outdoor weathering of plastics should be performed in accordance with ASTM D1435, which includes procedures for the exposure of specimens. Other ASTM test methods—listed in Chapters 3, 5 and 6—should be used for property evaluations. Testing should include the appropriate specimen identification parameters (Table 1-2), the common test parameters (Table 2-4), and those unique parameters, which are

1. *Location.* The city and state in which the specimens were exposed. A hot-dry, hot-humid, and temperate climate, such as is typically found in Arizona, Florida, and Massachusetts (or New York or New Jersey), respectively, should be used.

2. *Angle of Exposure.* All specimens should be exposed to face the equator at an angle of 45 deg.

3. *Time.* The exposure time in days should be 180, 360, 540, 720, and yearly thereafter up to 10 yr, as appropriate.

4. *Appearance.* The general change in specimens as compared to control specimens

5. *Tensile Property Change.* The average percent change in tensile strength, elongation, and modulus of elasticity as compared to control specimens. Testing should be performed in accordance with ASTM D638, as outlined in Chapter 3, by using a test speed of 5 mm/min (0.2 in./min) at a temperature of 23°C (73°F) in accordance with ASTM D3029, as described in Chapter 3.

6. *Electrical Property Change.* The average percent change in dielectric strength, dielectric constant, and volume resistivity as compared to control specimens. Testing should be performed in accordance with ASTMs D149, D150, and D257 by using nominal test conditions, as outlined in Chapter 5.

7. *Optical Property Change.* The average percent change in transmittance and yellowness index, as compared to control specimens. Testing should be performed in accordance with ASTMs D1003 and D1925 by using nominal test conditions, as outlined in Chapter 6.

Weathering data for plastics are extremely useful for any product intended for either limited or extended periods of outdoor exposure. The change in properties over time indicates the degree of degradation that would be expected as a function of time at the specific location. Test locations do not replicate the environment at other intended end use locations; thus the data have limited usefulness. The data, however, reflect a relative degree of suitability and establish the need for further material assessment by the designer. The data are useful in plotting the percent change of each property with time, and testing is recommended at only nominal test conditions. Although suitability at nominal conditions does not necessarily result in suitability at other test conditions, such as elevated temperature or strain rate, the data are indicative of long-term outdoor performance.

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GLOSSARY

A

Abbe constant. Ratio of refractivity of a material to its dispersion. Also called the Nu or Vee value. A calculated value from known indices of refraction (N_F , N_D , and N_C).

Ablative plastic. A material that absorbs heat (while part of it is being consumed by heat) through a thermal decomposition process known as pyrolysis, which takes place in the near surface layer exposed to heat.

Abrasion resistance. The resistance to mechanical wearing, grinding, scraping, or rubbing away of a material surface by friction, impact, or both measured in terms of material loss or change in an optical property.

Absorption. (1) The penetration into the mass of one substance by another. (2) The process by which energy is dissipated within a specimen placed in a field of radiation energy. Processes other than absorption occur, e.g., scattering; therefore, only a fraction of the energy removed from a beam is retained in the specimen.

Accelerated aging. Aging by artificial means to obtain an indication of how a material will behave under normal conditions over a prolonged period.

Acetal resins. Polymers containing the acetal linkage ($--CH_2--O--$), e.g., polyoxymethylene.

Acrylic resin. A synthetic resin prepared from acrylic acid or from a derivative of acrylic acid.

Acrylonitrile. A monomer with the structure $CH_2=CHCN$. Its copolymer with butadiene is nitrile rubber, and several copolymers with styrene exist that are tougher than polystyrene. Its homopolymer is also used as a synthetic fiber.

Acrylonitrile-butadiene-styrene (ABS). Blends or copolymers of polystyrene or styrene-acrylonitrile copolymer with butadiene-acrylonitrile rubber.

Aging. The change of a material with time under defined environmental conditions that lead to improvement or deterioration of properties.

Alkyd resins. Polyesters made from dicarboxylic acids and diols, primarily used as coatings, modified with vegetable oil, fatty acids, etc.

Alloy. Material made by blending polymers or copolymers with other polymers or elastomers under selected conditions, e.g., styrene-acrylonitrile copolymer resins blended with butadiene-acrylonitrile rubbers. *See also* Polyblends.

Amorphous phase. Devoid of crystallinity—no definite order. At processing temperature a plastic is normally in an amorphous state.

Angle of incidence. The angle between a ray or impinging liquid or solid and the normal to the plane or surface on which it is incident.

Annealing. A process of holding a material at an elevated temperature below its melting point. The objective is to permit stress relaxation without distortion of shape. This process is often used on molded articles to relieve stresses caused by flow into the mold.

Antioxidants. Substances that prevent or slow down oxidation of a polymeric material exposed to air.

Antistatic agents. Agents that minimize static electricity in plastics. Such agents are of two basic types: (1) metallic devices that come into contact with plastics and conduct static to earth. Such devices give complete neutralization at the time, but because they do not modify the surface of the material, it can become prone to further static during subsequent handling and (2) chemical additives that, when mixed with the compound during processing, give a reasonable degree of protection to the finished products.

Arc resistance. Time required for a given applied electrical voltage to render the surface of a material conductive because of carbonization by the arc discharge.

Artificial aging. The accelerated testing of plastic articles to determine changes in their properties based on exposure to varied environmental conditions. *See also* Aging.

Average molecular weight. Most synthetic polymers are a mixture of individual chains of many different sizes; hence a molecular weight assigned to such a mixture is of necessity an average molecular weight.

B

Birefringence. A measure of the anisotropy of a material characterized by having two refractive indexes that cause division of a single light beam into two separate beams.

Blow molding. A method of fabrication in which a parison, or hollow tube, is forced into the shape of the mold cavity by internal air pressure.

Branched. In molecular structure of polymers, this term refers to side chains attached to the main chain. Side chains are generally short. If long, they are called graft copolymers. *See also* Graft copolymer.

Breakdown voltage. The voltage required, under specific conditions, to cause the failure of an insulating material. *See also* Dielectric strength.

Brinell hardness. A method used to determine the hardness of a plastic material. Hardness is determined by forcing a hardened sphere under a known load into the surface of the material and measuring the diameter of the indentation resulting from the test. The Brinell number is obtained by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimeters. The result is a pressure, but the units are rarely stated.

Bulk density. The mass per unit volume of a molding powder as determined in a reasonably large volume.

Burning rate. A term describing the tendency of plastics articles to burn at given temperatures. Certain plastics, such as shellac, burn readily at comparatively low temperatures. Others melt or disintegrate without actually burning or burn only if exposed to direct flame. These are referred to as *self-extinguishing* (qv).

Butadiene. A diene monomer with the structure $\text{CH}_2=\text{CH}-\text{CH}=\text{CH}_2$. May be copolymerized with styrene and with acrylonitrile. Its homopolymer is used as a synthetic rubber.

C

Carbon black. A black pigment produced by the incomplete burning of natural gas or oil. It is widely used as a filler or pigment, particularly in the rubber industry. Because it possesses ultraviolet protective properties, it

is used in polyethylene systems such as cold water piping and black agricultural sheet.

Cast. (1) To form a "plastic" object by pouring a fluid monomer-polymer solution into an open mold where it finishes polymerizing; (2) to form plastic film and sheet by pouring the liquid resin onto a moving belt or by precipitation in a chemical bath.

Casting. (n) The finished product of a casting operation; should not be used for *molding* (qv).

Cellulose acetate. An acetic acid ester of cellulose obtained by the action, under rigidly controlled conditions, of acetic acid and acetic anhydride on purified cellulose usually obtained from cotton liners. All three available hydroxyl groups in each glucose unit of the cellulose can be acetylated, but in the preparation of cellulose acetate it is usual to acetylate fully and then to lower the acetyl value (expressed as acetic acid) to 52 to 56% by partial hydrolysis. When compounded with suitable plasticizers, the result is a tough thermoplastic material.

Cellulose acetate butyrate. An ester of cellulose made by the action of a mixture of acetic and butyric acids and their anhydrides on a purified cellulose. It is used in the manufacture of plastics that are similar in their general properties to cellulose acetate but are tougher and have better moisture resistance and dimensional stability.

Cellulose plastics. Plastics based on cellulose compounds, such as esters (cellulose acetate) and ethers (ethyl cellulose).

Cellulose propionate. An ester of cellulose made by the action of propionic acid and its anhydride on purified cellulose. It is used as the basis of a thermoplastic molding material.

Clarity. The characteristic of a transparent body that allows distinct high-contrast images or high-contrast objects to be observable through the body.

Cold flow. *See* Creep.

Cold molding. A procedure in which a composition is shaped at room temperature and cured by subsequent baking.

Color. Sensation resulting from stimulation of the eye by light containing different wavelengths. Produced in transparent plastics by dyes that restrict passage of all wavelengths except for the transmitted color.

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Compound. An intimately admixture of a polymer(s) with all the materials necessary for the finished product.

Compression mold. A mold that is open when the material is introduced and that shapes the material by heat and by the pressure of closing.

Compression molding. A technique of thermoset molding in which the molding compound (generally preheated) is placed in the open mold cavity, the mold is closed, and heat and pressure (in the form of a downward-moving ram) are applied until the material is cured.

Compressive strength. Pressure load at failure of a shaped specimen divided by a cross-sectional area of the specimen, which is usually the original sectional area.

Conditioning. The subjection of a material to a stipulated treatment to cause a uniform response to subsequent testing or processing. The term frequently is used to refer to the treatment given to specimens before testing.

Copolymer. A polymeric system that contains two or more monomeric units. *See also* Graft copolymer.

Corona resistance. A current passing through a conductor induces a surrounding electrostatic field. When voids exist in the insulation near the conductor, the high-voltage electrostatic field may ionize and rapidly accelerate some of the air molecules in the void. These ions then collide with the other molecules to ionize them and thereby "eat" a hole in the insulation. Resistance to this process is corona resistance.

Crazing. Fine cracks that may extend in a network on or under the surface or through a layer of a plastic material. Usually occurs in the presence of an organic liquid or vapor, with or without the application of mechanical stress.

Creep. The dimensional change with time of a material under load that follows the initial instantaneous elastic deformation. Creep at room temperature is called cold flow.

Critical angle. When light passes from a more dense to a less dense material, the angle (of incidence) at which all incident light is reflected back internally along the interface. Also referred to as total internal reflection. The critical angle is calculated from the index of refraction.

Cross-linking. The formation of primary valence bonds between polymer molecules. When extensive, as in thermosetting resins, cross-linking makes one infusible, insoluble supermolecule of all the chains.

Crystallinity. A state of molecular structure in some resins that denotes stereo-regularity and compactness of the molecular chains forming the polymer. Normally can be attributed to the formation of solid crystals having a definite geometric form.

Cure. Changing of physical properties of a material by chemical reactions such as polycondensation, addition polymerization or vulcanization; usually accomplished by the action of heat and catalysts alone or in combination, with or without pressure.

Cycle. The complete, repeating sequence of operations in a process or part of a process. In molding, the cycle time is the period, or elapsed time, between a certain point in one cycle and the same point in the next.

D

Degradation. A deleterious change in the chemical structure or inherent properties of a material.

Degree of polymerization (DP). The number of structural units, or -mers, in the polymer molecule in a particular sample. The value is obtained from the molecular weight of the polymer divided by that of the -mer. If "average" molecular weight is used, the value is the "average" DP. In most polymers the DP must reach several thousand if worthwhile physical properties are to result.

Density. Mass per unit volume of a substance expressed in grams per cubic centimetre (pounds-mass per cubic inch).

Dielectric. Insulating material. In radio-frequency preheating, dielectric may refer specifically to the material being heated.

Dielectric constant. Normally the dimensionless relative dielectric constant; for practical purposes, the ratio of the capacitance of an assembly of two electrodes separated solely by a dielectric material to its capacitance when the electrodes are separated solely by air.

Dielectric strength. The electric voltage gradient at which an insulating material is broken down, or "arced through", in volts per millimetre (volts per inch) of thickness.

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Differential scanning calorimetry. A technique for comparing the rate of heat inputs for a polymer sample with that of a standard, usually synthetic sapphire, for the same rate of temperature rise.

Differential thermal analysis. A technique to record the difference in temperature between a polymer sample and a standard, usually synthetic sapphire, for the same rate of heat input.

Dimensional stability. The ability of a plastic part to retain its original dimensions during its service life.

Discoloration. Any change from the original color of a plastic part. It may be caused by overheating, light exposure, irradiation, or chemical attack.

Dispersion. A material characteristic that causes some wavelengths of light to be transmitted with different angles of refraction. Thus a passage of a white light source results in a spectrum of colored bands diffracted in the order of their respective wavelength.

Dissipation. See Power factor.

Distortion. A visual aberration through a transparent material in the form of haze or fog; blurred, displaced, or deformed images. Distortion normally results from nonuniform material thickness, scattered light, or changes in refractive index that result from environmental effects.

Draft. The degree of taper of a side wall or the angle of clearance designed to facilitate removal of parts from a mold.

Ductility. The extent to which a solid material can be drawn into a thinner cross section.

Durometer hardness. Hardness of a material as measured by the Shore durometer.

Dynamic mechanical testing. A dynamic test in which a polymer is subjected to a cyclic, usually sinusoidal, deformation, and stress and strain are recorded continuously.

E

Elastic deformation. The part of the deformation of an object under load that is recoverable upon removal of the load.

Elasticity. The property of a material that causes it to recover its original size and shape after deformation. If

the strain is proportional to the applied stress, the material is said to exhibit Hookean, or ideal, elasticity.

Elastomer. A material that at room temperature stretches under low stress to at least twice its length and snaps back to the original length upon release of the stress.

Electromagnetic spectrum. A band of electromagnetic radiation referred to as a spectrum that extends from gamma rays, through X rays, ultraviolet radiation, visible radiation, infrared, microwave, and all other wavelengths of radio energy.

Elongation. The fractional increase in length of a material stressed in tension.

Encapsulating. Encasing an article (usually an electronic component) in a closed envelope of plastic by immersing the object in a casting resin and allowing the resin to polymerize or, if hot, to cool.

Environmental stress cracking (ESC). The susceptibility of a thermoplastic to crack or craze under influence of chemical treatment and/or mechanical stress.

Epoxy resins. Based on ethylene oxide, its derivatives, or homologs, epoxy resins form straight-chain thermoplastics and thermosetting resins, e.g., by the condensation of bisphenol and epichlorohydrin to yield a thermoplastic that is converted to a thermoset by active hydrogen-containing compounds, e.g., polyamines and dianhydrides.

Ethylene-vinyl acetate. Copolymer of ethylene and vinyl acetate having many of the properties of polyethylene but of considerably increased flexibility for its density; elongation and impact resistance are also increased.

Exotherm. (1) The temperature/time curve of a chemical reaction giving off heat, particularly the polymerization of casting resins. (2) The amount of heat given off. The term has not been standardized regarding sample size, ambient temperature, degree of mixing, etc.

Extrusion. The compacting of a plastic material and forcing it through an orifice more or less continuously.

F

Fabricate. To work a material into a finished form by machining, forming, or other operation, or to make flexible film or sheeting into end products by sewing, cutting, sealing, etc.

Fiber. This term usually refers to relatively short lengths of very small cross sections of various materials. Fibers can be made by chopping filaments (converting). Staple fibers may be 13 mm (0.5 in.) to several centimetres (inches) in length and usually from one to five denier.

Fiberglass. A widely used reinforcement for plastics that consists of fibers made from borosilicate and other formulations of glass. The reinforcements are in the form of roving (continuous or chopped), yarns, mat, milled, or woven fabric.

Filament winding. Roving or single strands of glass, metal, or other reinforcement are wound in a predetermined pattern onto a suitable mandrel. The pattern is designed to give maximum strength in the directions required. The strands can be run from a creel through a resin bath before winding, or pre-impregnated materials can be used. When the right number of layers has been applied, the wound mandrel is cured at room temperature or in an oven.

Filler. An inexpensive, inert substance added to a plastic to make it less costly. Fillers may also improve physical properties, particularly hardness, stiffness, and impact strength. The particles are usually small in contrast to those of *reinforcement* (qv), but there is some overlap between the functions of the two types of material.

Film. An optional term for sheeting having a nominal thickness not greater than 0.254 mm (0.01 in.).

Flame-retardant resin. A resin compounded with certain chemicals to reduce or eliminate its tendency to burn. For polyethylene and similar resins, chemicals such as antimony trioxide and chlorinated paraffins are useful.

Flammability. Measure of the extent to which a material will support combustion.

Flexibilizer. An additive that makes a resin or rubber more flexible. Also called plasticizer.

Flexural strength. The strength of a material in bending expressed as the tensile stress of the outermost fibers of a bent test sample at the instant of failure. With plastics this value is usually higher than the straight tensile strength.

Fluidized bed coating. A method of applying a coating of a thermoplastic resin to an article in which the heated article is immersed in a dense phase, fluidized bed of powdered resin and thereafter heated in an oven to provide a smooth, pinhole-free coating.

Fluorinated ethylenepropylene (FEP). A member of the fluorocarbon family of plastics. It is a copolymer to tetrafluoroethylene and hexafluoropropylene that possesses most of the properties of *polytetrafluoroethylene* (PTFE) (qv), and also has a melt viscosity low enough to permit conventional thermoplastic processing. Available in pellet form for molding and extrusion and as dispersions for spray or dipcoating processes.

Fluoroplastics (formerly called fluorocarbons). The family of plastics including polytetrafluoroethylene (PTFE), polychlorotrifluoroethylene (PCTFE), polyvinylidene fluoride, and fluorinated ethylene propylene (FEP). These plastics are characterized by properties including good thermal and chemical resistance and non-adhesiveness, and possess a low dissipation factor and low dielectric constant. Depending upon which of the fluorocarbons is used, they are available as molding materials, extrusion materials, dispersions, film, or tape.

Foamed plastics. Resins in sponge form. The sponge may be flexible or rigid, the cells closed or interconnected, and the density anything from that of the solid parent resin down to, in some cases, 32.04 kg/m³ (2 lbm/ft³). Compressive strength of rigid foams is fair, and it makes them useful as core materials for sandwich structures. Both types are good heat barriers.

Foil decorating. Molding paper, textile, or plastic foil printed with compatible inks directly into a plastic part so that the foil is visible below the surface of the part as integral decoration.

Friction welding. A method of welding thermoplastic materials in which the heat necessary to soften the components is provided by friction.

Furan resins. Dark-colored, thermosetting resins that are primarily liquids ranging from low-viscosity polymers to thick, heavy syrups. Based on furfuryl or furfuryl alcohol.

G

Glass transition. The change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one. This transition generally occurs over a relatively narrow temperature region and is similar to the solidification of a liquid to a glassy state; it is not a phase transition. Not only do

hardness and brittleness undergo rapid changes in this temperature region, but other properties such as thermal expansibility and specific heat also change rapidly. This phenomenon has been called second-order transition, glass transition, rubber transition, and rubbery transition.

Glass transition temperature (T_g). The temperature region in which the glass transition occurs. The measured value of the glass transition temperature depends to some extent on the method of test. *See also* Glass transition.

Gloss. Ratio between the reflected flux scattered within a certain solid angle to the incident flux. Used to indicate relative surface shininess, distinctness of reflected images, and texture.

Graft copolymer. A chain of one type of polymer to which side chains of a different or the same type are attached or grafted, e.g., simultaneous polymerization of butadiene and styrene monomers. *See also* Copolymer.

H

Hardness. The resistance of a plastic material to compression and indentation. Among the most important methods of testing this property are Brinell hardness, Rockwell hardness, and Shore hardness. *See also* Brinell hardness and Rockwell hardness and Shore hardness.

Haze. The cloudy or turbid aspect or appearance of an otherwise transparent specimen that is caused by light scattered from within the specimen or from its surface.

Heat distortion point. The temperature at which a standard test bar deflects 0.254 mm (0.01 in.) under a stated pressure of either 0.455 or 1.82 MPa (66 or 264 psi).

Heat sealing. A method of joining plastic films by simultaneous application of heat and pressure to areas in contact. Heat may be supplied conductively or dielectrically.

Homopolymer. A polymer consisting of only one monomeric species.

Hot gas welding. A technique used to join thermoplastic materials (usually sheet). The materials are softened by a jet of hot air from a welding torch and joined together at the softened points. Generally a thin rod of the same material is used to fill and consolidate the gap.

Hot stamping. Engraving operation for marking plastics in which roll leaf is stamped with heated metal dies

onto the face of the plastics. Ink compounds can also be used. By means of felt rolls, ink is applied to type, and by means of heat and pressure, the type is impressed into the material and leaves the marking compound in the indentation.

Hydrolysis. Chemical reaction of a substance with water.

Hygroscopic. Tends to absorb moisture.

I

Impact resistance. Relative susceptibility of plastics to fracture by shock, e.g., as indicated by the energy expended by a standard pendulum-type impact machine in breaking a standard specimen in one blow.

Impact strength. (1) The ability of a material to withstand shock loading. (2) The work done in fracturing, under shock loading, a specified test specimen in a specified manner.

Injection blow molding. A blow-molding process in which the parison to be blown is formed by injection molding.

Injection molding. A molding procedure whereby a heat-softened plastic material is forced from a cylinder into a relatively cool cavity that gives the article the desired shape.

Insulation resistance. The electrical resistance of an insulating material to a direct voltage. It is determined by measuring the leakage of current that flows through the insulation.

Izod impact test. A test designed to determine the resistance of a plastics material to shock loading. It involves the notching of a specimen, which is then placed in the jaws of the machine and struck with a weighted pendulum. *See also* Impact strength.

L

Light resistance. The ability of a plastic material to resist fading after exposure to sunlight or ultraviolet light. Nearly all plastics tend to darken under these conditions.

Light scattering. The deviation of that portion of the transmitted light due to optical inhomogeneities in the material. The scattering effect is normally referred to as haze (qv).

Loss factor. The product of the power factor and the dielectric constant (qv).

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Luminous transmittance. The ratio of the luminous flux transmitted by a body to the flux incident upon it.

M

Matched metal molding. Method of molding reinforced plastics between two close-fitting metal molds mounted in a hydraulic press.

Melamine formaldehyde resin. A synthetic resin derived from the reaction of melamine (2,4,6-triamino-1,3,5-triazine) with formaldehyde.

Melt index. The amount in grams of a thermoplastic resin that can be forced through a 2.1-mm (0.083 in.) orifice when subjected to 21.2 N (4.8 lbf) force in 10 min at 190°C (374°F).

-Mer. The repeating structure unit of any high polymer.

Metallizing. Applying a thin coating of metal to a nonmetallic surface. May be done by chemical deposition or by exposing the surface to vaporized metal in a vacuum chamber.

Methyl methacrylate. A colorless, volatile liquid derived from acetone cyanohydrin, methanol, and dilute sulphuric acid and used in the production of *acrylic resins* (qv).

Methylpentene polymer. A thermoplastic material based on 4-methylpentene-1 and having low specific gravity (0.83), 90% optical transmission, 390°C (734°F) thermal range, and excellent electrical properties.

Modulus of elasticity. Stress/strain ratio in a plastic material that is elastically deformed.

Mohs' value. A measure of hardness based on a scale established in 1822 by Frederick Mohs that gives a relative ranking of minerals in the order in which one will scratch another.

Moisture-vapor transmission. The rate at which water vapor permeates through a plastic film or wall at a specified temperature and relative humidity.

Mold. (v) To shape plastic parts or finished articles by heat and pressure. (n) (1) The cavity or matrix into which the plastic composition is placed and from which it takes its form. (2) The assembly of all the parts that function collectively in the molding process.

Mold shrinkage (*shrinkage, contraction*). The difference in dimensions, expressed in mm/mm (in./in.), between a molding and the mold cavity in which it was molded.

Both the mold and the molding are at normal room temperature when measured.

Molecular weight. A measure of the chain length for the molecules that comprise the polymer. Refers to the average weight of the molecules in the mixture of different sizes that normally exist.

Molecular weight distribution. A measure of the frequency of occurrence of the different molecular weight chains contained in a homologous polymeric system. The ratio of the weight average molecular weight is sometimes used as an indication of the breadth of the distribution.

Monomer. A relatively simple compound that can react to form a polymer. *See also* Polymer.

Morphology. Refers to the overall form of a polymer structure, i.e., crystallinity, branching, molecular weight, etc.

N

Nylon. The generic name for all synthetic fiber-forming polyamides. They can be formed into monofilaments and yarns characterized by great toughness, strength and elasticity, high melting point, and good resistance to water and chemicals. The material is widely used for bristles in industrial and domestic brushes and for many textile applications; it is also used in injection molding gears, bearings, combs, etc.

O

Olefins. A group of unsaturated hydrocarbons of the general formula C_xH_{2y} and named after the corresponding paraffins by the addition of "ene" or "ylene" to the stem. Examples are ethylene and pentene-1.

Organic. A material or compound composed of hydrocarbons or their derivatives, or those materials found naturally or derived from plant or animal origin.

Orientation. Alignment of the crystalline structure in polymeric materials in order to produce a highly uniform structure. Can be accomplished by cold drawing or stretching in fabrication.

P

Permanent set. The increase in length, expressed as a percentage of the original length, by which an elastic material fails to return to original length after being stressed for a standard period of time.

Permeability. (1) The passage or diffusion of vapor, liquid, or solid through a barrier without physically or chemically affecting the barrier. (2) The rate of such passage.

Phenolic resin. A synthetic resin produced by the condensation of phenol with formaldehyde. Phenolic resins form the basis of a family of thermosetting molding materials, laminated sheet and oven-drying varnishes. They are also used as impregnating agents and as components of paints, varnishes, lacquers, and adhesives.

Plastic. (*adj*) Pliable and capable of being shaped by pressure.

Plastic deformation. A change in dimensions of an object under load that is not recovered when the load is removed; opposed to elastic deformation.

Plasticizer. Chemical agents added to plastic compositions to improve flow and processability and to reduce brittleness. These improvements are achieved by lowering the glass transition temperature.

Polyamide. A polymer in which structural units are linked by amide grouping. Many polyamides are fiber formers.

Polyblends. A mechanical (nonchemical) mixture of two or more polymers, e.g., polystyrene and rubber.

Polycarbonate resins. Polymers derived from the direct reaction between aromatic and aliphatic dihydroxy compounds with phosgene or by the ester exchange reaction with appropriate phosgene-derived precursors. Structural units are linked by carbonate groups.

Polyester. A resin formed by the reaction between a dibasic acid and a dihydroxy alcohol—both organic—or by the polymerization of a hydroxy carboxylic acid. Modification with multifunctional acids and/or alcohols and some unsaturated reactants permit cross-linking to thermosetting resins.

Polyethylene. A thermoplastic material composed solely of ethylene. It is normally a translucent, tough, waxy solid that is unaffected by water and by a large range of chemicals.

Polyimide resins. Aromatic polyimides made by reacting pyrometallic dianhydride with aromatic diamines. Characterized by high resistance to thermal stress.

Applications include components for internal combustion engines.

Polyisobutylene. The polymerization product of isobutylene. It varies in consistency from a viscous liquid to a rubberlike solid with corresponding variation in molecular weight from 1000 to 400,000.

Polymer. A high-molecular-weight compound, natural or synthetic, whose structure can usually be represented by a repeated small unit, the -mer, e.g., polyethylene, rubber, and cellulose. Synthetic polymers are formed by addition or condensation polymerization of monomers. Some polymers are elastomers, some are plastics, and some are fibers.

Polymerization. A chemical reaction in which the high-molecular-weight molecules are formed from the original substances. When two or more monomers are involved, the process is called copolymerization or heteropolymerization.

Polymethyl methacrylate. A thermoplastic polymer synthesized from methyl methacrylate. It is a transparent solid with exceptional optical properties and good resistance to water. It is obtainable in the form of sheets, granules, solutions, and emulsions. Polymethyl methacrylate is extensively used for aircraft domes, lighting fixtures, decorative articles, etc.; it is also used in optical instruments and in surgical appliances.

Polyphenylene oxide. A polyether of 2,6-dimethyl-phenol synthesized via an oxidative coupling process by means of air or pure oxygen in the presence of a copper-amine complex catalyst.

Polypropylene. A tough, lightweight, rigid plastic made by the polymerization of high-purity propylene gas in the presence of an organometallic catalyst at relatively low pressures and temperatures.

Polysiloxanes. Polymers that contain the Si-O linkage. Usually synthesized by the polycondensation of silanols.

Polystyrene. A water-white thermoplastic produced by the polymerization of styrene (vinyl benzene). The electrical insulating properties of polystyrene are extremely good, and the material is relatively unaffected by moisture.

Polysulfides. Polymers containing sulfur and carbon linkages. An example of this type of polymer is Thiokol® rubber, which is synthesized from organic dihalides and sodium polysulfide.

Polysulfone. A polymer containing the sulfone linkage. These thermoplastic materials exhibit exceptional high-temperature and low-creep properties, have arc resistance, are self-extinguishing, and may be molded and extruded.

Polytetrafluoroethylene (PFTE) resins. Members of the *fluoroplastic (qv)* family of plastics made by the polymerization of tetrafluoroethylene. PTFE is characterized by its extreme inertness to chemicals, very high thermal stability, and low frictional properties. Among the applications for these materials are bearings, fuel hoses, gaskets, tapes, and coatings for metal and fabric.

Polyurethane resins. A family of resins produced by reacting diisocyanates in excess with glycols to form polymers having free isocyanate groups. Under the influence of heat or certain catalysts, these groups will react with each other or with water, glycols, etc., to form a thermoset.

Polyvinyl chloride (PVC). A thermoplastic polymer synthesized from vinyl chloride; a colorless solid with outstanding resistance to water, alcohols and concentrated acids and alkalies. It is obtainable in the form of granules, solutions, and pastes. Compounded with plasticizers, it yields a flexible material (plastisol) superior to rubber in aging properties. Widely used for cable and wire coverings and in making protective garments.

Polyvinyl chloride acetate. A thermoplastic copolymer of vinyl chloride and vinyl acetate; a colorless solid with good resistance to water, concentrated acids, and alkalies. It is obtainable in the form of granules, solutions and emulsions. Compounded with plasticizers, it yields a flexible material superior to rubber in aging properties. Widely used for cable and wire coverings and in protective garments.

Polyvinylidene chloride. A thermoplastic polymer of vinylidene chloride (1,1-dichloroethylene). It is a white powder with a softening temperature of 185° to 200° C. (365° to 392° F) The material is also supplied as a copolymer with acrylonitrile or vinyl chloride and yields products that range from the soft flexible type to the rigid type. Polyvinylidene chloride is also known as saran.

Postforming. The forming, bending, or shaping of thermoset laminates that have been heated to make them flexible before the final thermosetting reaction has occurred. On cooling, the formed laminate retains the contours and shape of the mold over which it has been formed.

Potting. Similar to *encapsulating (qv)* except that steps are taken to insure complete penetration of all the voids in the object before the resin polymerizes.

Power factor. In a perfect condenser the current leads the voltage by 90 deg. When a loss takes place in the insulation, the absorbed current, which produces heat, disrupts the 90-deg relationship in proportion to the current absorbed by the dielectric. The power factor is the cosine of the angle between voltage applied and the current resulting. Measurements are usually made at million-cycle frequencies.

Prepolymer. (n) A chemical intermediate whose molecular weight is between that of the monomer or monomers and the final polymer or resin.

Q

Quench (thermoplastics). A process of shock cooling thermoplastic materials from the molten state.

R

Reflectance. Ratio of the luminous reflected flux or light to incident flux. The amount of reflected light from a surface is related mathematically and is dependent on the angle of incidence and the refractive index of the transparent material as well as the smoothness and polish of the surface.

Refractive index. Ratio of the measured angle of incidence to the angle of refraction when light passes from one medium to another. The value expressed in tables is termed the absolute index because the first medium is air, which is equivalent to measurement in a vacuum. The standard test procedure is ASTM D542.

Reinforced molding compound. Compound containing resin and a reinforcing filler that is supplied in the form of ready-to-use materials.

Reinforcement. A strong inert material put into a plastic to improve its strength, stiffness, and impact resistance. Reinforcements are usually long fibers of glass, sisal, cotton, etc., in woven or nonwoven form. To be effective, the reinforcing material must form a strong adhesive bond with the resin.

Residual stress. The stresses remaining in a plastic part as a result of thermal or mechanical treatment.

Resin. Any of a class of solid or semisolid organic products of natural or synthetic origin, generally of high molecular weight, and with no definite melting point. Most resins are *polymers (qv)*.

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Resistivity. The ability of a material to resist passage of electrical current either through its bulk or on a surface. The unit of volume resistivity is the ohm-cm, of surface resistivity, the ohm.

Resolution. The capability of an optical system to transmit clear and distinguishable parts of an object. Loss of resolving power is due to poor surface finish and poor quality material. Resolution is synonymous with clarity.

Rheology. The study of flow of polymeric materials on a macroscopic and microscopic level.

Rockwell hardness. A common method of testing a plastic material for resistance to indentation in which a diamond or steel ball is used under pressure to pierce the test specimen. The load used is expressed in kilograms (pounds-mass). A 10-kg (22.0-lbm) weight is first applied and the degree of penetration noted. The so-called major load, 60 to 150 kg (132.3 to 330.7 lbm), is next applied, and a second reading is obtained. The hardness is then calculated as the difference between the two loads and expressed with nine different prefix letters to denote the type of penetrator used and the weight applied as the major load.

Rotational casting (or molding). A method used to make hollow articles from plastisols and latices. Plastisol is charged into a hollow mold capable of being rotated in one or two planes. The hot mold fuses the plastisol into a gel after the rotation has caused it to cover all surfaces. The mold is then chilled and the product stripped out.

S

Self-extinguishing. A somewhat loosely used term describing the ability of a material to cease burning once the source of flame has been removed.

Shear strength. (1) The ability of a material to withstand shear stress. (2) The stress at which a material fails in shear.

Shear stress. The stress development in a polymer melt when the layers in a cross section are gliding along each other or along the wall of the channel (in laminar flow). The stress is defined by the force divided by the sheared area.

Sheet (thermoplastic). A flat section of a thermoplastic resin with the length considerably greater than the width and 0.254 mm (10 mil) or greater in thickness.

Shore hardness. A method of determining the hardness of a plastic material. The device used consists of a small conical hammer fitted with a diamond point and acting in a glass tube. The hammer is made to strike the material under test, and the degree of rebound is noted on a graduated scale. Generally the harder the material, the greater will be the rebound.

Shrinkage. Contraction of a molded material upon cooling or of a casting upon polymerizing.

Sink mark. A shallow depression or dimple on the surface of an injection-molded part due to collapsing of the surface following local internal shrinkage after the gate seals. May also be an incipient short shot.

Softening range. The range of temperatures in which a plastic changes from a rigid to a soft state. Actual values will depend on the method of test. Sometimes erroneously referred to as softening point.

Solution. Homogeneous mixture of two or more components, e.g., gas dissolved in gas or liquid or a solid dissolved in a liquid.

Solvation. The process of swelling, gelling, or dissolving of a resin by a solvent or plasticizer.

Specific gravity. The density (mass per unit volume) of any material divided by that of water at a standard temperature, usually 4°C (39.2°F). The density of water is nearly 1.00 g/cm³; therefore, density in g/cm³ and specific gravity are nearly equal numerically.

Specific heat. The ratio of the quantity of heat required to raise the temperature of a mass one degree to that required to raise the temperature of an equal mass of water one degree.

Specular transmittance. The transmittance value obtained when the measured transmittance flux includes only that transmitted in essentially the same direction as the incident flux.

SPI tolerances. A presentation of workable tolerance values that can be achieved in molding various materials.

Spin welding. A process of fusing two objects together by forcing them together while one of the pair is spinning until frictional heat melts the interface. Spinning is then stopped, and pressure held until they are frozen together.

Stabilizer. An ingredient used in the formulation of some polymers to assist in maintaining the physical and chemical properties of the compounded materials at their initial values throughout the processing and service life of the material, e.g., heat and *ultraviolet (qv)* stabilizers.

Stress crack. External or internal crack in a plastic caused by tensile stresses. The development of such a crack is frequently accelerated by the environment to which the plastic is exposed. The stresses that cause cracking may be present internally or externally or a combination of both. Appearance of a network of fine cracks is called *crazing (qv)*.

Surface resistivity. The electrical resistance between opposite edges of a unit square of insulation material. It is commonly expressed in ohms.

T

Tensile bar (specimen). A compression- or injection-molded specimen of specified dimensions used to determine the tensile properties of a material.

Tensile strength. The pulling stress in pascals (pounds per square inch) required to break a given specimen. Area used in computing strength is usually the original, rather than the necked-down, area.

Terpolymer. A polymeric system that contains three monomeric units, e.g., ABS (acrylonitrile, butadiene, styrene) terpolymer.

Thermal conductivity. Ability of a material to conduct heat; quantity of heat that passes through a unit cube of a substance in a unit of time when the difference in temperature between the two faces is one degree.

Thermal expansion (coefficient of). The fractional change in length (sometimes volume specified) of a material for a unit change in temperature. Values for plastics range from 10^{-5} to 2×10^{-4} mm/mm $^{\circ}$ C (1.8×10^{-5} to 36×10^{-5} in./in. $^{\circ}$ F).

Thermal stress cracking (TSC). Crazing and cracking of some thermoplastic resins resulting from overexposure to elevated temperatures.

Thermoforming. Any process of forming thermoplastic sheet that consists of heating the sheet and pulling it down onto a mold surface.

Thermoplastic. (adj) Capable of being repeatedly softened by heat and hardened by cooling. **(n)** A material having a linear macromolecular structure that will repeatedly soften when heated and harden when cooled. Typical

of the thermoplastics family are the styrene polymers and copolymers, acrylics, cellulose, polyethylenes, vinyls, nylons, and the various fluorocarbon materials.

Thermoset. A material that will undergo a chemical reaction by the action of heat, catalysts, ultraviolet light, etc., leading to a relatively infusible and cross-linked state. Typical of the plastics in the thermosetting family are the epoxies, glyptals, ureaformaldehyde resins, and phenolics.

Thixotropic. Said of materials that are gel-like at rest but fluid when agitated. Liquids containing suspended solids are apt to be thixotropic. Thixotropy is desirable in paints.

Torsion pendulum. A dynamic mechanical test used to determine the elastic and loss modulus of plastics over a range of temperatures.

Transfer molding. A method of molding thermosetting materials in which the plastic is first softened by heat and pressure in a transfer chamber then forced at high pressure through suitable sprues, runners, and gates into a closed mold for final curing.

Transmittance. Ratio of the luminous flux or light transmitted through a material to that of the incident flux. Also referred to as diffuse transmittance, luminous transmittance. When the light source is monochromatic light, it is called *specular transmittance (qv)*.

Transparency. A characteristic of a material that allows various wavelengths of energy to pass through with a negligible portion of it scattered. Optical transparency is measured by its light-scattering characteristics (haze) and refractive index at the visible wavelengths of light. Of related interest in plastics is the transparency or transmittance at ultraviolet and infrared wavelengths.

U

Ultrasonic sealing. A film-sealing method in which sealing is accomplished through the application of vibratory mechanical pressure at ultrasonic frequencies (20 to 40 kHz). Electrical energy is converted to ultrasonic vibrations through the use of either a magnetostrictive or piezoelectric transducer. The vibratory pressures at the film interface in the sealing area develop localized heat losses that melt the plastic surfaces and thereby effect the seal.

Ultraviolet (UV). Zone of invisible radiation beyond the violet end of the spectrum of visible radiation. UV radiation is of shorter wavelength than visible; there-

fore, it is of higher energy. Energy is sufficient to initiate some chemical reactions and to degrade most plastics.

Urea-formaldehyde resin (*urea resin*). A synthetic thermoset resin derived from the reaction of urea (carbamide) with formaldehyde or its polymers.

UV stabilizer (*ultraviolet*). Any chemical compound that, when admixed with a thermoplastic material, selectively absorbs UV rays.

V

Vacuum forming. Method of sheet forming in which the plastic sheet is clamped in a stationary frame, heated, and drawn down by a vacuum into a mold. Loosely, the term is sometimes used to refer to all sheet-forming techniques involving the use of vacuum and stationary molds.

Volume resistivity (*specific insulation resistance*). The electrical resistance between opposite faces of a 1-centimetre (0.39-inch) cube of insulating material. It is measured under prescribed conditions using a direct current potential after a specified time of electrification. It is commonly expressed in ohm-centimeters. The recommended test is ASTM D257.

W

Wavelength. The length of a wave measured from one point on the wave to a corresponding point on the next wave, which denotes the various forms of radiant energy that comprise the electromagnetic spectrum.

Weathering. The process of degradation and decomposition that results from exposure to the atmosphere, to chemical action, and to the action of other natural environmental factors.

Weatherometer. An instrument used to subject articles to accelerated weathering conditions, e.g., rich UV source and water spray.

White light. An energy source that produces radiant energy having the same color sensation to the eye as average noon sunlight.

Y

Young's modulus of elasticity. In an ideal (Hookean) elastic deformation in which the stress is proportional to the strain, Young's modulus of elasticity E in tension or compression is the ratio of stress to axial strain.

Yield value (*yield strength*). The lowest stress at which a material undergoes plastic deformation. Below this stress the material is elastic, above it, viscous.

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